Z. KHUDYAKOV

REPAIR OF POWER TRANS- FORMERS

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ИЗДАТЕЛЬСТВО МИР

З. И. ХУДЯКОВ

РЕМОНТ ТРАНСФОРМАТОРОВ

ИЗДАТЕЛЬСТВО «ВЫСШАЯ ШКОЛА» · МОСКВА

Z. KHUDYAKOV

REPAIR OF POWER TRANSFORMERS

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The Greek Alphabet

Α α Alpha	Ι ι Iota	Ρ ρ Rho
Β β Beta	Κ κ Kappa	Σ σ Sigma
Γ γ Gamma	Λ λ Lambda	Τ τ Tau
Δ δ Delta	Μ μ Mu	Υ υ Upsilon
Ε ε Epsilon	Ν ν Nu	Φ φ Phi
Ζ ζ Zeta	Ξ ξ Xi	Χ χ Chi
Η η Eta	Ο ο Omicron	Ψ ψ Psi
Θ θ ϑ Theta	Π π Pi	Ω ω Omega

The Russian Alphabet and Transliteration

А а a	К к k	Х х kh
Б б b	Л л l	Ц ц ts
В в v	М м m	Ч ч ch
Г г g	Н н n	Ш ш sh
Д д d	О о o	Щ щ shch
Е е e	П п p	ъ ″
Ё ё e	Р р r	ы y
Ж ж zh	С с s	ь ′
З з z	Т т t	Э э e
И и i	У у u	Ю ю yu
Й й y	Ф ф f	Я я ya

На английском языке

Contents

Preface

The rapid growth of the capacity of power stations and supply networks, and their integration into power systems by means of long-distance, high- and super-high-capacity transmission lines, require reliable and uninterrupted operation of every piece of electrical equipment, power transformers included.

On its way from the generating station to the consumer, electric power is transformed several times. Today, when hardly a single electrical installation can do without a power transformer, the uninterrupted operation of the transformers, whose total capacity is several times the installed generating capacity, cannot be overestimated.

Year after year, transformer-building works raise their output of increasingly perfect transformers, and the unit capacity of power transformers grows higher in line with this rise. At present, the maximum unit capacity of three-phase transformers is 630 MV A at 500 kV on the high-voltage side; that of autotransformers is to come to 1 million kV A in the near future.

Transformers are sufficiently reliable in operation, but as the pool of operating power transformers grows larger, so does the number of transformers which, for one reason or another, stand in need of repair. Old, unreliable transformers have to be repaired as well. Besides, there are cases where their characteristics can no longer meet the more stringent technical requirements of the day, hence the need for modernization.

Low- and medium-capacity transformers are usually repaired at specialized works, while high-capacity ones, directly on site. Some transformer parts are repaired at transformer-building works.

In-situ repairs require highly skilled personnel capable of organizing their workplace correctly. It is especially important that the workers should be skilled in several trades—electrician and winder, electrician and welder, etc.

For a timely and efficient repair work it is essential that the personnel have a high standard of technical knowledge. This book outlines the amount of technical knowledge necessary for electricians specializing in transformer repairs and is intended for training at vocational schools or on the job.

CHAPTER ONE

An Outline of Transformers

1.1. Application of Transformers

Electrical energy generated by fuel-fired (thermal) power stations usually located near large fuel deposits and by hydro-electric stations built in regions where water power resources are available has to be transmitted to industrial centres which may lie hundreds and thousands of kilometres away from the stations, hence the need for vast transmission lines between the generating plants and the consumers.

It is a well-known fact that when current is transmitted over a line, some of the power it carries is dissipated as heat in the line conductors. This loss grows higher as the current and the resistance of the conductors are increased. It is not economical to try to reduce the loss by solely decreasing the conductor resistance, because this would require a substantial increase in the cross-sectional area of the conductors, entailing a large consumption of costly nonferrous metals.

It is precisely to reduce the power loss and consumption of nonferrous metals that the transformer is used. The transformer, while leaving the transmitted power unchanged, decreases current by increasing voltage, and the loss which is proportional to the square of the current (I^2R loss) is thus sharply reduced. For example, a ten-fold increase in the supply voltage reduces the power loss by a factor of 100.

At the beginning of a power transmission line the voltage is raised by step-up transformers, and at the end of the line it is lowered by step-down transformers to a value convenient for the consumers (from 127 V to a few kilovolts). Electric power is distributed among the consumers (works, factories, residential areas, etc.) through transformer substations.

The prime role in the present-day power engineering is played by power transformers, i.e., transformers used to raise or lower voltages in the supply networks of power systems

which serve to transmit electric power over great distances and distribute it among the consumers. Power transformers are notable for their high power capacity and operating voltage.

Since electricity has to be conveyed over thousands of kilometres — to the integrated power grid, the load centres, and directly to numerous minor consumers — it has to be transformed four or even five times, hence the need to install a large number of step-up and step-down transformers. Also,

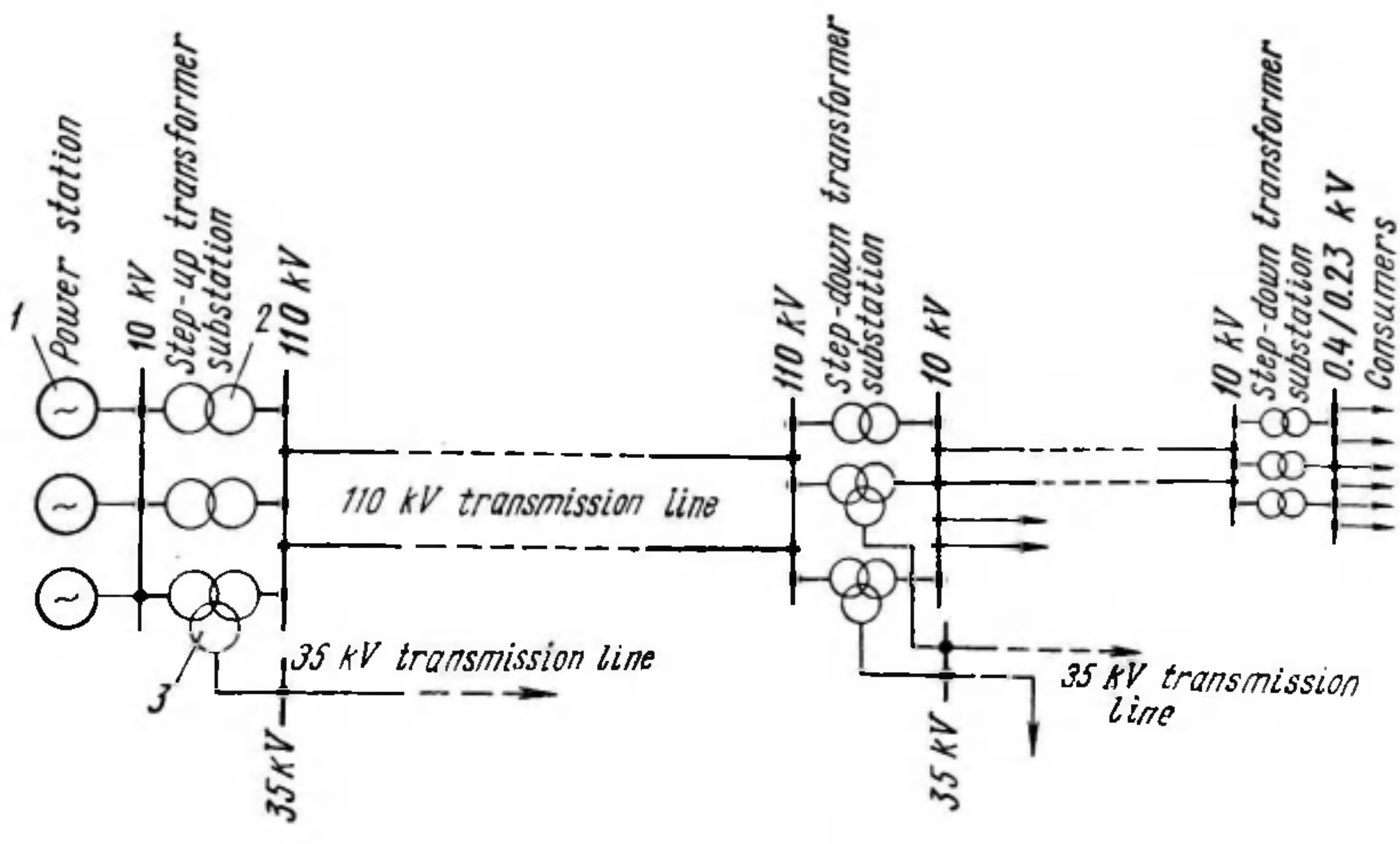


Fig. 1.1. Single-line diagram of a transmission and distribution network

1—generator; 2—two-winding transformer; 3—three-winding transformer

it should be noted that at each transformation stage operating at progressively lower voltage the total capacity of power transformers is usually greater than that at the preceding stage. Therefore, in any power system the installed transforming capacity is six or seven times the installed generating capacity. As an example, Fig. 1.1 shows the layout of a transmission and distribution network.

Supply networks operating at a voltage of 220 kV and higher make wide use of autotransformers. Such transformers have two or more windings conductively connected so that

there is some winding portion common to both the primary and the secondary circuits.

Besides power transformers and autotransformers, there are a great variety of special transformers, including electric-furnace, rectifier, welding, regulating, testing, traction, marine, mining, and instrument transformers. Numerous types of transformers find application in communications equipment, automatic and telecontrol systems, domestic appliances, and so on. Today, there is hardly a single electrical installation operating without a transformer. The capacities and voltages of existing transformers vary over a very wide range — from a few fractions of a kilovolt-ampere to hundreds of thousands of kilovolt-amperes and from a few fractions of a volt to hundreds of kilovolts.

Autotransformers and some special transformers will be onsidered in greater detail later in the text.

1.2. Principle of Operation of the Transformer and Basic Definitions

The transformer is an electromagnetic apparatus consisting of two or more independent electric circuits (windings) linked by a common magnetic circuit (core), which, by electromagnetic induction, converts one or more alternating-current systems to one or more other alternating-current systems without the use of rotating parts, and, in particular, is intended for transforming electric power at one voltage to electric power at some other voltage. For its operation the transformer depends on the phenomenon of electromagnetic induction which is the generation of an electromotive force (emf) in a closed conductive circuit by a change in the magnetic flux linking that circuit.

Figure 1.2 shows a schematic diagram of a simple single-phase transformer. Core *3* made up of thin, insulated laminations of electrical-sheet steel carries two windings (coils) *1* and *2* which are insulated from each other. If one of the windings, say winding *1*, is supplied with alternating voltage V_1, current I_x will flow in it, producing magnetic flux Φ which varies at the same frequency as voltage V_1 does.

Since the permeability of steel is 800 to 1000 times that of air, a major part of the magnetic flux, which is called the

main flux, has its path through the core. The other part of the flux (referred to as the leakage flux $\Phi_{l,1}$), much smaller in magnitude than the main one, does not link magnetically with winding *2* and has its path through air. The leakage flux takes no part in voltage (energy) transformation.

According to the law of electromagnetic induction, the periodically varying main magnetic flux Φ linking both windings *1* and *2* induces an emf in each. Let us designate

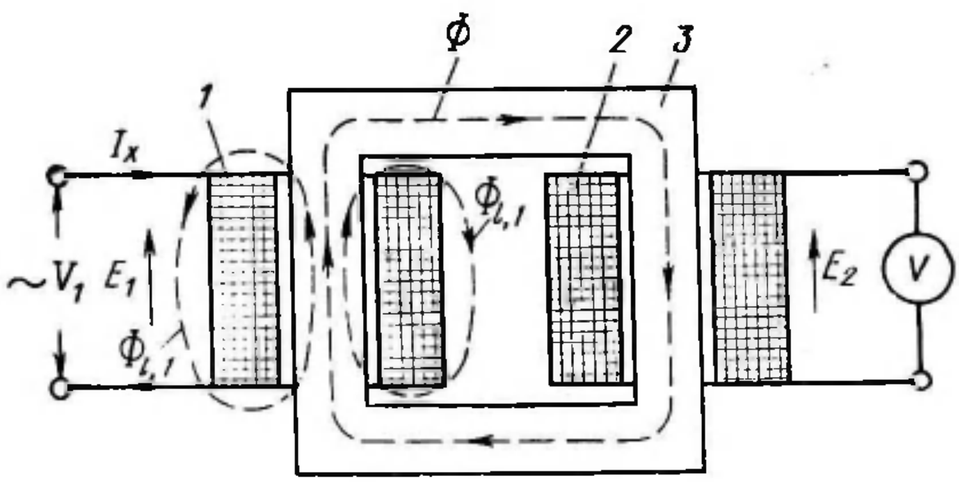


Fig. 1.2. Simple single-phase transformer
1—primary winding; *2*—secondary winding; *3*—core

these emf's as E_1 and E_2. Electromotive force E_2 can be measured with a voltmeter connected across winding *2*. If winding *2* is connected across some load, this will give rise to a flow of current through the load, and this current will cause an increase in the current flowing in winding *1*.

Thus, the apparatus considered transforms the electrical energy supplied to winding *1* first to electromagnetic energy and then to the electrical energy consumed by the load circuit connected across winding *2*.

The transformer winding to which the a.c. power being transformed is supplied is referred to as the *primary winding*, while the other, from which the transformed a.c. power is drawn, is called the *secondary winding*.

Electromotive Forces Induced in the Transformer Windings

The magnitudes of emf's E_1 and E_2 induced in the primary and secondary windings (see Fig. 1.2) are measured in

volts and may be calculated by the following formulas:

$$E_1 = 4.44 f n_1 \Phi_m \text{ (volts)}$$

$$E_2 = 4.44 f n_2 \Phi_m \text{ (volts)}$$

where f = frequency of alternating current, Hz
n_1 and n_2 = number of turns in the primary and secondary windings
Φ_m = peak (maximum) value of magnetic flux, Wb

Electromotive force E_1 induced in the primary winding is practically equal to the applied voltage; the magnitude of secondary emf E_2 depends on the number of turns in the secondary winding. An increase in the number of turns on the secondary side causes an increase in the secondary emf, and vice versa. In practice, to calculate the *emf*'s induced in the transformer windings use is made of a formula in which frequency is taken at 50 Hz (mains frequency). Then

$$E = 222 n A_{core} B_{core} \times 10^{-4} \text{ (volts)}$$

where n = number of winding turns
A_{core} = net cross-sectional area of the core limb, cm^2
B_{core} = magnetic induction in the core limb, T

The net cross-sectional area of the core is the area of the core steel less the lamination insulation.

The emf per turn, e_t, is given by

$$e_t = 222 A_{core} B_{core} \times 10^{-4} \text{ (volts)}$$

The voltage induced per turn (e_t) is the same for both the primary and secondary windings since they are linked by one and the same flux. This is a very important transformer characteristic which is widely used in calculations. For example, if e_t (volts) and A_{core} (square centimetres) are known, it is an easy matter to calculate the magnetic induction in the core:

$$B_{core} = (e_t \times 10^4)/222 A_{core} \text{ (teslas)}$$

The units of measurement here are given in accordance with the SI system (USSR Standard 9867—61). In this system the unit of magnetic flux is the weber (Wb) having the dimension of volt-second (V s), and the unit of magnetic induction, the tesla (T) with the dimension of volt-second per square metre (V s/m^2).

To convert magnetic flux in maxwells (the cgs system) to webers, one should use the following relation:

$$1 \text{ Wb} = 1 \text{ V s} = 10^8 \text{ Mx}$$

A conversion factor of 10^4 should be used to convert induction in gausses (the cgs system) to teslas:

$$1 \text{ T} = 10^4 \text{ Gs}$$

Transformation Ratio

A very important characteristic of the transformer is the transformation ratio (k) which is the ratio of the emf induced in the high-voltage (HV) winding to that induced in the low-voltage (LV) winding, so, it is always greater than unity. The transformation ratio is widely used in calculations.

Under no-load conditions, it may safely be assumed that the *emf*'s induced in the transformer windings are equal to the voltages across these windings, i.e.,

$$E_1 = V_1 \text{ and } E_2 = V_2$$

Hence, if, say, the primary winding having n_1 turns is the HV winding and the secondary with n_2 turns, the LV winding we then may write

$$k = E_1/E_2 = V_1/V_2 = n_1/n_2$$

whence

$$V_1 = kV_2 \text{ and } n_1 = kn_2$$

Thus, knowing the transformation ratio and the voltage on the secondary side of a transformer, we can easily find the voltage on the primary side, and vice versa. This equally applies to the numbers of turns in the windings.

Basic Definitions

According to their operating voltage, transformers are divided into classes. The transformer winding of a higher voltage class is referred to as the *high-voltage* (HV) *winding*, and that of a lower voltage class, as the *low-voltage* (LV) *winding*. The winding of a voltage class intermediate between those of the HV and LV windings is called the *medium-voltage* (MV) *winding* (in three-winding transformers).

A transformer whose core carries two independent windings is called the *two-winding* transformer, while that with three independent windings on its core is referred to as the *three-winding* transformer. High-capacity power transformers often have three windings — HV, MV, and LV. One of these is the *primary*, and the two others are the *secondaries*.

A transformer whose primary is the LV winding is called the *step-up* transformer, and that with the HV primary is known as the *step-down* transformer.

A transformer with a single-phase magnetic field produced in its magnetic circuit (core) is referred to as the *single-phase* transformer, while the *three-phase* transformer is the one in whose magnetic circuit a three-phase magnetic field is produced.

To improve the electrical insulation of the current-carrying components of a transformer and its cooling conditions, the transformer windings, together with the core, are placed in a tank filled with transformer oil. Such transformers are called *oil-immersed* or *oil-cooled.* Some special transformers use an incombustible synthetic liquid — askarel — instead of the oil. Transformers operating in air (not immersed in oil) are called the dry-type or air-cooled.

Each transformer has a nameplate on which the rated values defining its operating conditions are indicated.

The *rated* values, or ratings, are the numerical values of electrical quantities, such as capacity, voltages, currents, frequency, etc., assinged to the transformer by the designer to define its working in conditions specified by a pertinent standard. These values form the basis for the manufacture, testing and operating of the transformer.

The rated capacity of the transformer is usually expressed as its apparent power in kilovolt-amperes (the kV A rating). Transformers are built for certain standard rated capacities and voltages. The rated primary voltage is the one for which the primary winding of the transformer is designed. The rated secondary voltage is the voltage developing across the secondary winding when the transformer primary is supplied with the rated voltage under conditions of no load. The rated currents are determined by the corresponding rated voltages and the kV A rating of the transformer. In the USSR, the rated frequency for transformers is 50 Hz.

1.3. Power Transformer Performance

No-Load (Open-Circuit) Characteristics. No-Load Current and Losses

If rated alternating voltage V_1 is impressed on a transformer winding, say, the primary winding $A—X$ having n_1 turns (Fig. 1.3*a*) whilst the secondary winding is open-circuited, the transformer is said to be operating under conditions of no load.

Current $I_{no-load}$ flowing in the primary of the transformer on no load is known as the *no-load current.* Its magnitude is small in comparison with that of the rated primary current: 2-3.5% in low-capacity power transformers and 0.5-1.5% in high-capacity transformers of Soviet make.

The reactive component of the no-load current produces the main magnetic flux Φ in the core and a weak leakage flux $\Phi_{l,1}$ which causes an inductive reactance to come into play in the primary circuit. The resistive component of the no-load current, amounting to not more than 10% of the reactive component, has but a negligible effect on the latter and causes only a resistance voltage drop across the primary winding. Therefore, the no-load current is customarily called the *exciting current.*

The no-load transformer transfers no electrical energy since the secondary winding having n_2 turns is open-circuited. The active power consumed by the transformer is dissipated as heat in the core steel and partially in the primary winding. These power losses as a whole are referred to as the *no-load losses* of the transformer and designated as $P_{no-load}$.

The I^2R loss (copper loss) in the primary winding due to the no-load current is low because the current is small, therefore, this loss is disregarded and the active power consumed by the transformer under no-load conditions is considered to be dissipated only as losses in the core steel, i.e.,

$$P_{no-load} = P_{core}$$

The power losses in the core steel are caused by its cyclic magnetization (reversal of magnetic field sense at twice the supply frequency) and by eddy currents. The reversal of magnetization is accompanied by the generation of heat in

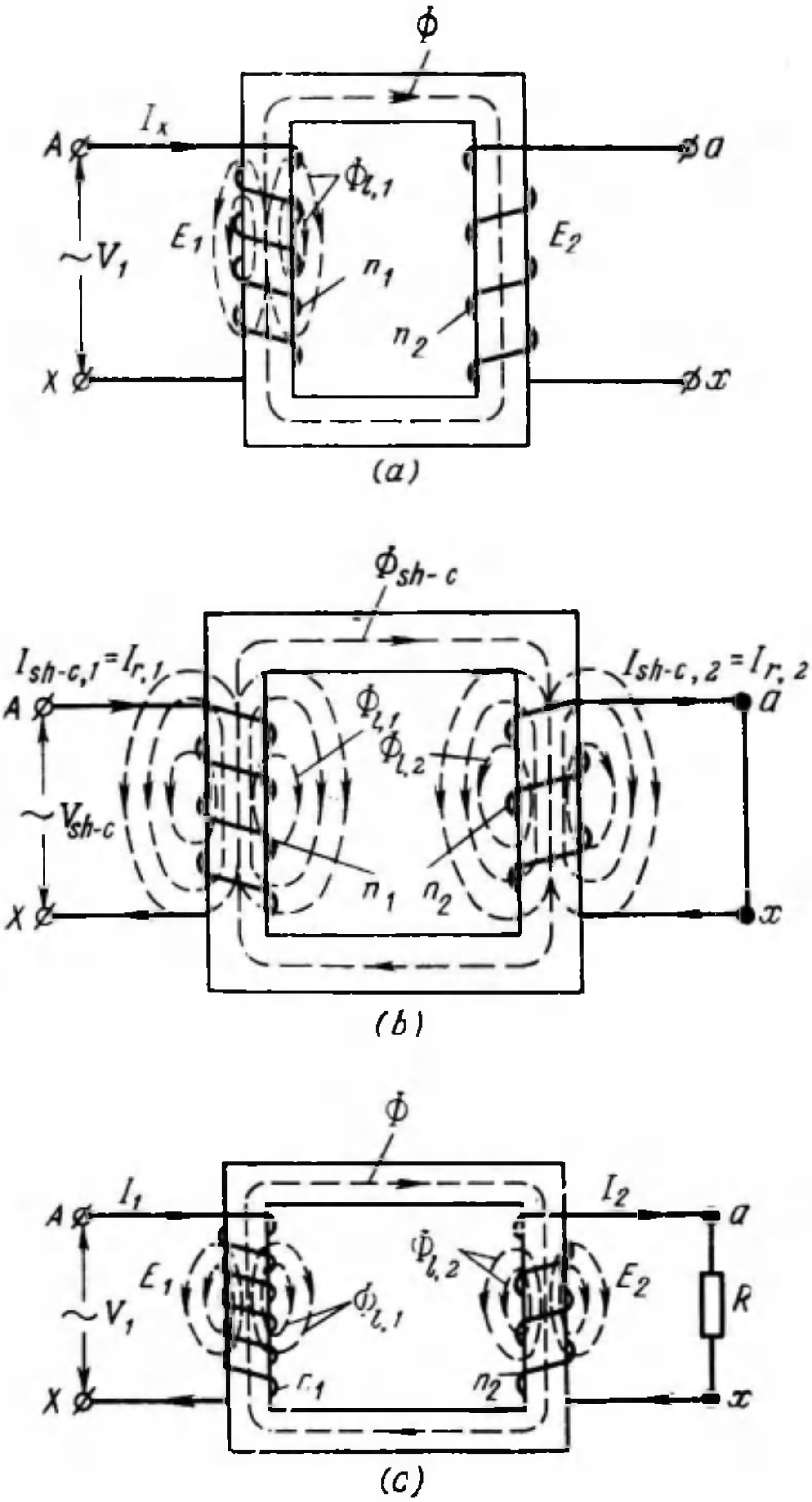


Fig. 1.3. Illustrating power transformer performance

(*a*) no-load operation; (*b*) short-circuit test; (*c*) on-load operation

the core and requires power expenditure, as in any other type of work. The loss of power in the transformer core due to the cyclic magnetization of the core steel is called the *hysteresis loss.*

The transformer core is made of metal and operates in an alternating magnetic field. According to the law of electromagnetic induction, this induces currents in it. These currents flow in planes perpendicular to the direction of the magnetic flux and are referred to as *eddy currents*. The thicker the core laminations and the lower their resistivity, the greater the magnitude of these currents. Eddy currents are also called parasitic, for when their paths are completed through the core steel, they heat it, thereby causing some waste of energy.

If the steel core were made solid, eddy currents would grow enormous and cause prohibitive heating of the core. To reduce the eddy-current loss, transformer cores are made up of 0.35-0.5 mm thick steel laminations (also called punchings or stampings) insulated one from another. The insulating film prevents the flow of current from lamination to lamination.

In practice, the hysteresis and eddy-current losses are not taken separately, and one simply considers what is called the *core* (or *iron*) *loss*, bearing in mind that this is the sum of the hysteresis and eddy-current losses. It is customary to estimate the core loss in terms of specific loss, i.e., the loss of power per kilogram of the core steel. The loss per kilogram of a given grade of steel depends on its permeability, resistivity, frequency of alternating current, magnetic induction, and lamination thickness.

During normal operation, the no-load losses of a transformer come only to 0.3-0.5% of its rated capacity. Nevertheless, no effort is spared to minimize these losses. The point is that the induction in the core, and consequently the core loss, practically remain the same whatever the operating conditions of the transformer (i.e., on no load or under load) and, as a result, the total annual losses of power amount to a substantial figure. For transformer steel, the specific loss at the 50-Hz standard frequency and an induction of 1-1.5 T ranges from a few fractions of a watt to several watts per kilogram. The specific loss values at 50 Hz for various grades of steel, as dependent on the steel thickness and induction, are specified in USSR Standard 802-58.

The no-load losses grow materially as the induction in the core is increased. This may stem from inadequate stacking

of the core (reduced number of laminations) or rewinding of the windings (reduced number of turns) during repairs. The ageing of the core steel, and the mechanical damaging of the core laminations and their insulation as a result of negligence on the part of repair-men contribute to an increase in the core loss. As will be recalled, electrical-sheet steel partially loses its valuable magnetic properties when subjected to sharp blows and bending. All this causes a wasteful increase in the no-load current and power drawn by the primary winding of the transformer from the current source.

Short-Circuit Characteristics. Short-Circuit (Impedance) Voltage and Losses

When one of the transformer windings is short-circuited and a voltage is applied to the other, the transformer is said to be operating on a *short circuit*. If such a short circuit occurs during operation of the transformer at the rated voltages, the short-circuit currents arising in the windings exceed the rated ones 10-15 times and more. Under such conditions, heavy mechanical stresses develop in the windings and the temperature of the latter rises. The operation of the transformer on a short circuit is very harmful, and a special protecting device is required, which must switch off the transformer in a fraction of a second.

Consider the short-circuit transformer test (Fig. 1.3*b*) which helps determine one of the basic transformer characteristics—the short-circuit (or impedance) voltage V_{sh-c}. If one of the transformer windings, say, the secondary, is short-circuited (see Fig. 1.3*b*) while a reduced voltage is applied to the primary winding, and if this voltage is gradually increased, then at a certain value V_{sh-c} of this voltage, which is called the *short-circuit voltage*, in the primary and secondary windings will circulate short-circuit currents $I_{sh-c,\,1}$ and $I_{sh-c,\,2}$ equal in magnitude to the rated primary and secondary currents $I_{r,\,1}$ and $I_{r,\,2}$.

The short-circuit voltage of a transformer is usually expressed as a percentage of the rated primary voltage:

$$v_{sh\text{-}c}\,\% = (V_{sh\text{-}c}/V_{r,\,1}) \times 100$$

where v_{sh-c} = short-circuit voltage, %
V_{sh-c} = short-circuit voltage, V
$V_{r,1}$ = rated primary voltage, V

The short-circuit voltage is a very important operating characteristics. The equality of the short-circuit voltages of transformers is one of the conditions requisite for their possible parallel operation. Voltage v_{sh-c} is indicated on the nameplate of each transformer. Its value, depending on the type and capacity of transformer, is specified by the pertinent standards and ranges from 5 to 7% for low- and medium-capacity power transformers and from 6 to 17% and more for high-capacity transformers.

During the short-circuit test, the applied short-circuit voltage of low magnitude produces a weak flux Φ_{sh-c} in the transformer core. Besides, the rated currents flowing in the primary and secondary windings produce leakage fluxes $\Phi_{l,1}$ and $\Phi_{l,2}$ whose paths are partly in air and partly in the metal components of the transformer.

The leakage fluxes produced in the transformer operating on a short circuit give rise to a substantial inductive reactance, thereby limiting the short-circuit current in the windings and protecting them against excessive heating and mechanical damage. It is mainly the reactance voltage drop across the windings that determines the magnitude of the short-circuit transformer voltage. The higher the v_{sh-c}, the less the danger that the windings will be damaged by the mechanical forces developing under short-circuit emergency conditions.

However, voltage v_{sh-c} should not exceed a certain value, lest an inadmissibly high reactance voltage drop across the secondary winding due to the high inductive reactance caused by the leakage fluxes should reduce secondary voltage V_2 and consequently, the useful power available to the consumers. In addition, the leakage fluxes having their paths partly in the metal components of the transformer cause extra eddy-current and hysteresis losses (also known as the stray losses) which reduce the efficiency of the transformer.

When designing a transformer, the magnitude of v_{sh-c} is selected so as to make the transformer as strong mechanically and thermally as possible on the one hand, and have the

maximum possible efficiency on the other, i.e., to strike a balance between these two conflicting requirements.

Voltage V_{sh-c} fed to the transformer during the short-circuit test is by a factor of 5 to 20 lower than the rated voltage, depending on the type of transformer; therefore, the exciting flux Φ_{sh-c} which takes its path in the core amounts to not more than 5% of the main magnetic flux. For this reason, the core loss is disregarded, and power P_{sh-c} consumed by the transformer under such conditions is considered to be dissipated completely as the copper loss in the primary and secondary windings and stray hysteresis and eddy-current losses due to leakage fluxes in the steel structural components (tank walls, yoke clamps, etc.). Since these losses have the same magnitude as in the case of the transformer operation under full load, they are frequently referred to as the *load losses*.

Characteristics of the Loaded Transformer

The transformer is said to be operating under load (see Fig. 1.3*c*) when voltage V_1 is applied to the primary winding and the secondary winding is completed through a load (shown as resistance R). The primary winding is electromagnetically linked with the secondary, and the flow of current in the loaded secondary winding (as in short-circuit test) will automatically change the current in the primary winding since magnetomotive forces (mmf) in any electromagnetic system are always in equilibrium.

The voltage applied across the primary winding remains practically constant: therefore, counter electromotive force E_1 in the primary on load will not change and will remain the same as on no load. Owing to this fact, exciting current $I_{no-load}$ and secondary emf E_2 will also remain unvaried. Consequently, at a given primary voltage V_1, which does not depend on the load, the magnitudes of primary emf E_1, main flux Φ, no-load current $I_{no-load}$ and secondary emf E_2 in the loaded transformer remain the same as under conditions of no load.

By analogy with the law of equilibrium of electromotive forces, a magnetomotive force acting in a magnetic circuit is always equalized by the counter magnetomotive force of

this circuit. Under conditions of no load, the primary mmf $I_{no-load}\, n_1$ is consumed mainly in producing the main magnetic flux Φ in the core. But under load, the primary mmf $I_1 n_1$ must equalize the secondary mmf $I_2 n_2$ due to the load current, which has the opposite direction, and provide for mmf $I_{no-load} n_1$ producing the main magnetic flux Φ in the magnetic circuit. The primary and secondary leakage fluxes may be disregarded because they are very weak in comparison with the main flux, and one may consider that the primary ampere-turns $\dot{I}_1 n_1$ in the loaded transformer are equal to the sum of the secondary ampere-turns $\dot{I}_2 n_2$ and the exciting ampere-turns $\dot{I}_{no-load} n_1$, i.e.,

$$\dot{I}_1 n_1 = \dot{I}_2 n_2 + \dot{I}_{no\text{-}load} n_1$$

The dots above the current symbols show that the currents are vector quantities which are added vectorially (with account being taken of their phase displacement in circuits containing resistances and inductive reactances). It is quite obvious that the total losses in the loaded transformer are the losses represented by the sum of the no-load losses (mainly the core loss) and the load losses which include the copper loss in the HV and LV windings due to the load current and stray loss due to leakage or stray fluxes in the windings, tank walls, yoke clamps and other metal parts of the transformer.

Efficiency of the Transformer

Both the iron and copper losses (no-load and load losses) occur during the normal operation of the transformer under load. If the no-load and short-circuit losses, as well as the useful power available at the 'secondary terminals of the transformer are known, it is possible to determine its efficiency and to judge of its economy. The per cent efficiency of the transformer is given by

$$\eta\% = (P_2/P_1) \times 100$$

where P_1 = power taken by the primary winding, kW
P_2 = useful power available at the secondary terminals, kW

Since the power fed to the transformer equals the power drawn from the secondary, P_2, plus the total losses of the transformer, the expression for the per cent efficiency may be written as

$$\eta\,\% = [P_2/(P_2 + P_{sh\text{-}c} + P_{no\text{-}load})] \times 100$$

where P_{sh-c} = short-circuit (load) losses, kW
$P_{no-load}$ = no-load losses (core loss), kW

Transformers have a fairly high efficiency which ranges from 98.5 to 99.3% and higher, depending on the rated capacity and load.

1.4. Single- and Three-Phase Transformers

Low-capacity single-phase transformers are most frequently used as welding, measuring, testing, isolating and other types of transformers, including those used in house-

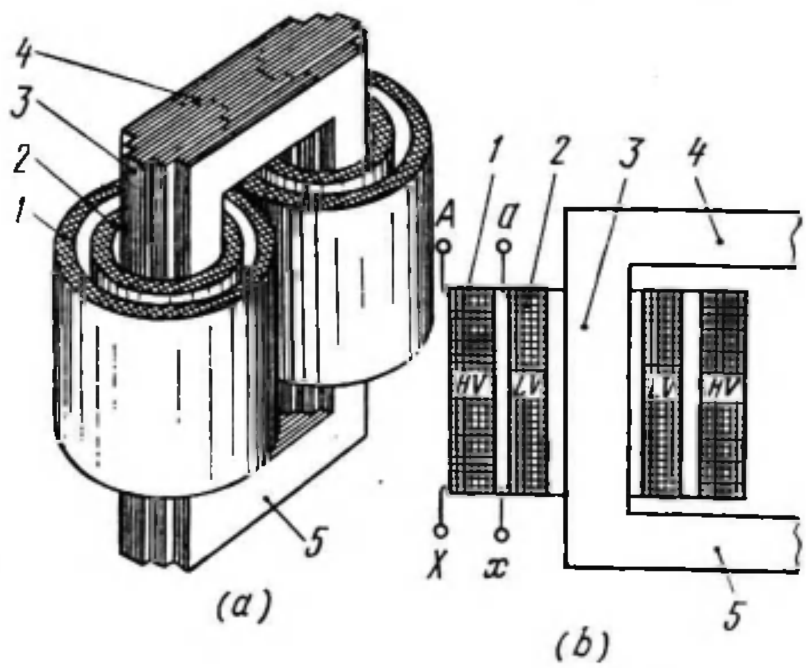


Fig. 1.4. Arrangement of windings on transformer core limbs

(*a*) external view; (*b*) schematic diagram; *1*—HV winding; *2*—LV winding; *3*—core limbs; *4*—top yoke; *5*—bottom yoke

hold appliances. High-capacity single-phase power transformers of the high-voltage type are used for transforming three-phase power.

To diminish leakage fluxes, the primary and secondary, HV and LV, windings are arranged concentrically on the core, as is shown in Fig. 1.4. The core of single-phase transformers usually consists of top yoke *4*, bottom yoke *5*, and two limbs or legs *3*. Each leg carries two or three windings of various voltages (LV, MV or HV). The windings of respective voltages carried by both core legs are connected

either in series or in parallel. The leads for connecting the transformer into the circuit are tapped from the common points of the winding connections (A-X; a-x).

Consider possible connections of the windings arranged on the core limbs of a single-phase transformer whose schematic diagram is illustrated in Fig. 1.5*a*. Assume that voltage V is applied across terminals A-X of primary winding *3*, and that main magnetic flux Φ is produced in the core.

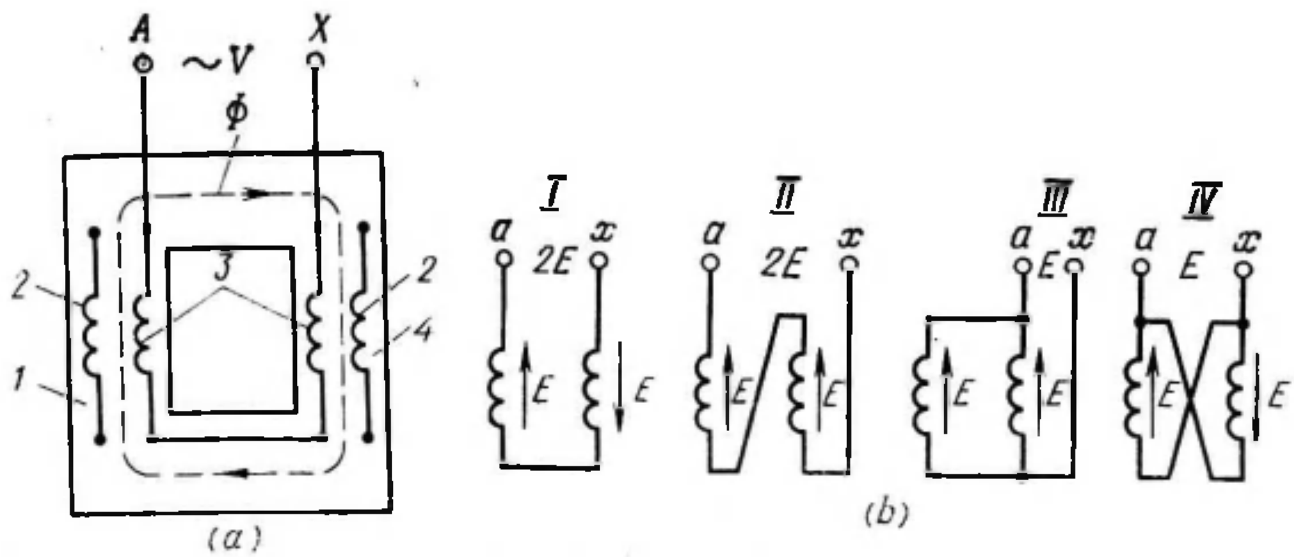


Fig. 1.5. Winding connection diagrams for a single-phase transformer

(*a*) schematic transformer diagram; (*b*) winding connection diagrams; *1*—core limb *A*; *2*—secondary windings; *3*—primary windings; *4*—core limb *X*; *I*—series connection of windings of the same hand; *II*—series connection of windings of opposite hands; *III*—parallel connection of windings of opposite hands; *IV*—parallel connection of windings of the same hand

Depending on their direction (right- or left-hand), secondary windings *2* carried by core limbs A and X may be connected in various ways (see Fig. 1.5*b*). Electromotive force E will be induced in each of the windings, but the resultant emf obtained across terminals a-x will be either $2E$ or E, depending on the winding connection selected. If the windings are wrongly connected, the resultant emf will be zero and the transformer will operate on a short circuit.

As is seen from Fig. 1.5*b*, when the windings of the same hand are connected in series, their resultant emf equals $2E$, and when they are connected in parallel, it is equal to E. The opposition of the emf's induced in the windings of the same hand is explained by the fact that the magnetic flux has different directions in the core limbs. The primary windings may have similar connections.

To transform three-phase power by means of single-phase transformers, use is made of what is called the three-phase transformer group. Such a group comprises three single-phase transformers whose terminals are connected so as to form a three-phase circuit. One of possible versions of such

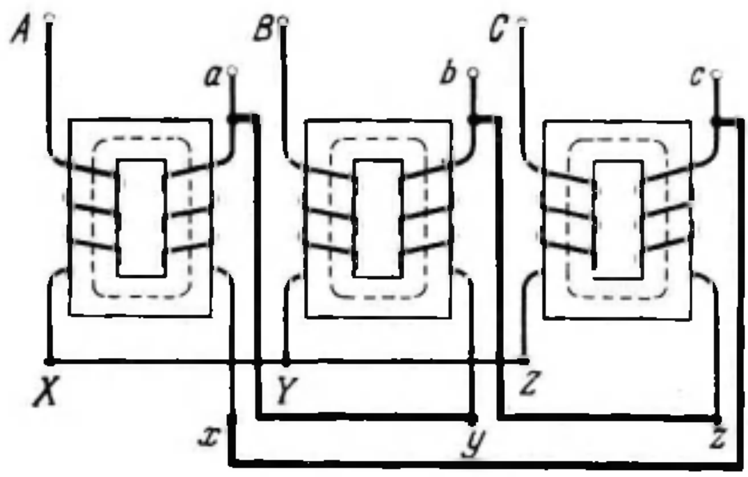


Fig. 1.6. Schematic diagram of three single-phase transformers connected into a star-delta three-phase group

a connection is shown in Fig. 1.6. In this case, common to all the three transformers is the electric circuit alone, while the electromagnetic circuits of the transformers operate individually.

Combining the electromagnetic and electrical systems of three single-phase transformers into a single system makes it possible to obtain a three-phase transformer as a single unit. This can be achieved if the three single-phase transformer cores are put together in a triangle, as is shown schematically in Fig. 1.7, and the windings of the component limbs are made common. The three-limb core thus obtained is a symmetrical electromagnetic system, since the paths of all the magnetic fluxes are of the same length.

In practice, however, the cores of three-phase transformers are, as a rule, made asymmetrical: three limbs *1* (see Fig. 1.8) are placed in a single plane and joined by means of common yokes, the top yoke *2* and bottom yoke *3*. It can be seen from the figure that the path *A-B* of the magnetic flux in the centre limb is shorter than those in the extreme limbs. The asymmetry of the magnetic circuit somewhat affects the no-load currents of individual phases.

The windings arranged on the limbs of a three-limb core are called the *phase windings of the transformer*. Their connection into three-phase circuits makes a three-phase transformer. The cost of manufacturing and installing a single three-

phase transformer is less than that of three single-phase units providing the same power capacity. Present-day power transformers are predominantly made as three-phase units. The mass of a single three-phase transformer is 30-35% less than the total mass of three single-phase transformers connected

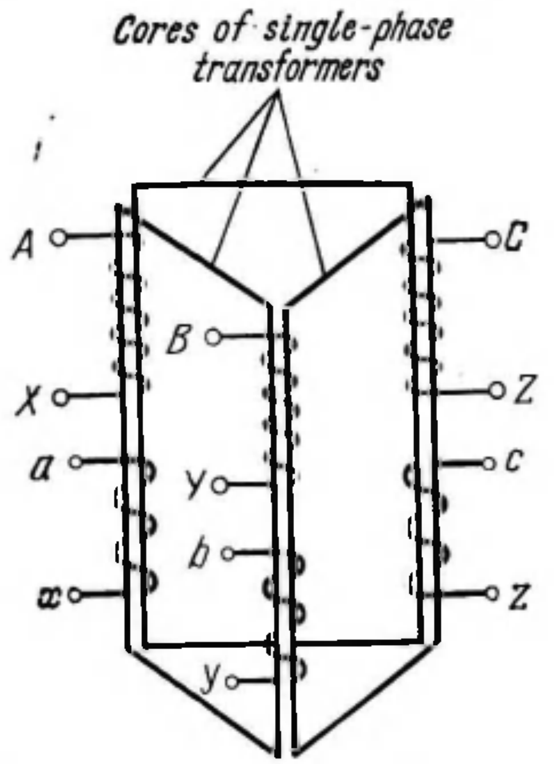


Fig. 1.7. Schematic diagram of a three-phase transformer with a symmetrical core

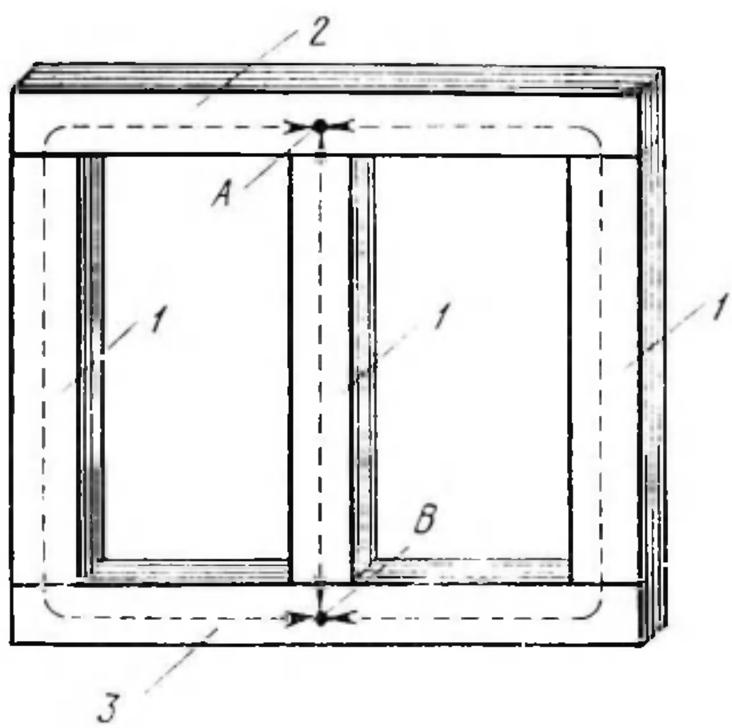


Fig. 1.8. Three-phase transformer core
1—limbs; 2—top yoke; 3—bottom yoke

in a three-phase group. In addition, three-phase transformers are more economical in operation and maintenance.

The use of single-phase transformers in a three-phase group is sometimes justified in view of the fact that simultaneous failure of several phases is hardly possible, therefore it is quite enough to have one stand-by single-phase transformer in order to restore a damaged phase, whereas a failure of a three-phase transformer will cause complete loss of power supply. Single-phase transformers are only employed in cases involving very high capacities where the transportation and installation of huge three-phase units would entail great difficulties.

The power capacity of transformers is expressed in terms of their apparent power (kV A rating) S. It is measured in volt-amperes (V A), kilovolt-amperes (kV A) and megavolt-amperes (MV A). The kV A rating of one phase of a three-

phase transformer is given by

$$S = V_{ph} I_{ph} \times 10^{-3} \text{ kV A}.$$

where V_{ph} and I_{ph} = rated phase voltage and current in volts and amperes, respectively

The kV A rating of a three-phase transformer, expressed in terms of the rated line voltage and current, is

$$S = \sqrt{3}\, VI \times 10^{-3} \text{ kV A}$$

where $\sqrt{3}$ = coefficient taking account of the relation between the phase and line voltages or currents in a three-phase system
V = rated line voltage, V
I = rated line current, A

1.5. Circuit Symbols. Types and Phase-Displacement Groups of Transformer Winding Connections

Under USSR Standard 11677—75, the starts and finishes of power transformer windings and their intermediate taps are designated in a specified manner.

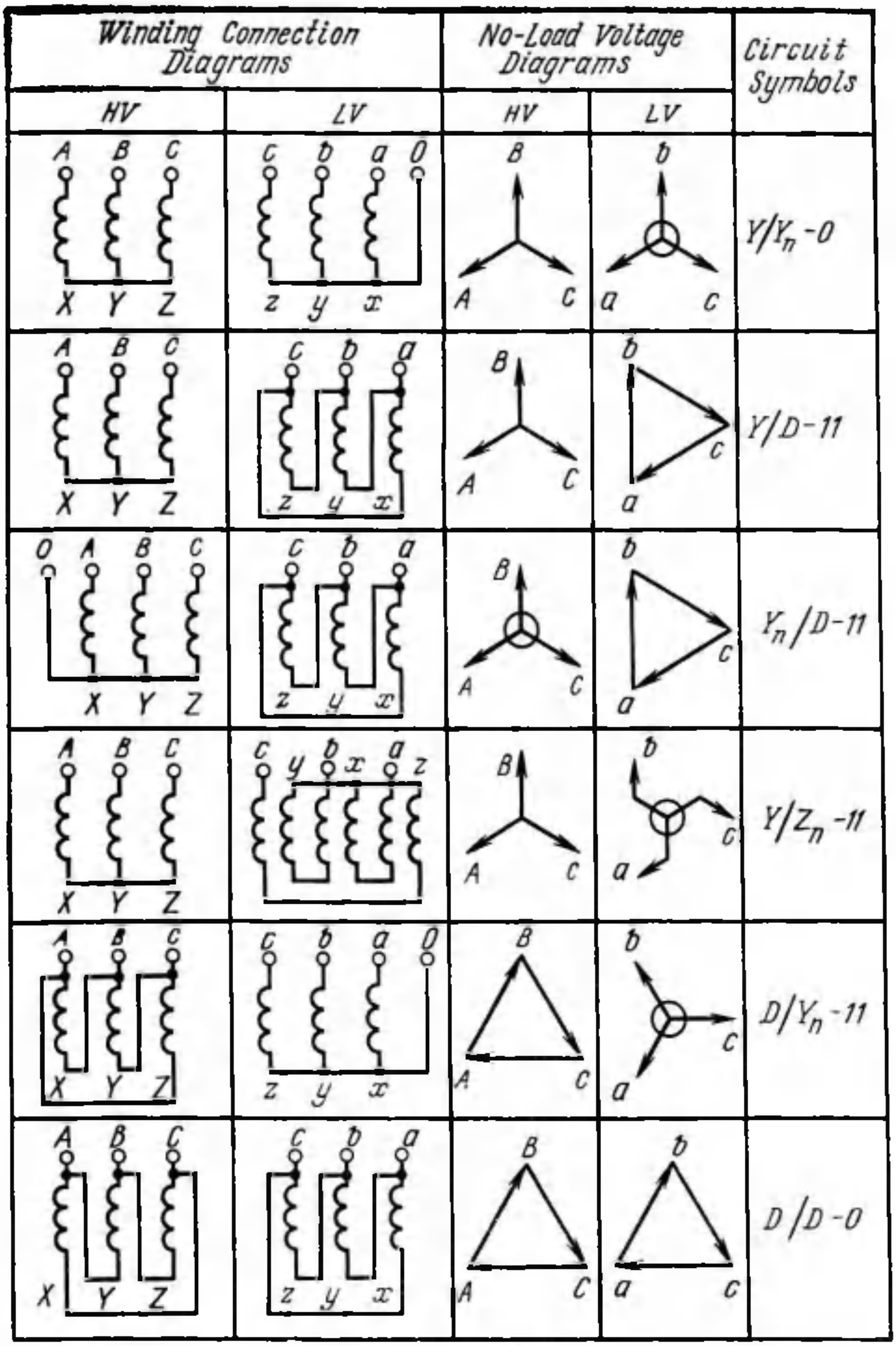
The starts of the HV phase windings of three-phase transformers are designated by capital letters A, B and C, and their finishes, by letters X, Y and Z, respectively. The alteration of phases A, B, C run from left to right as viewed from the HV terminals. The starts of the LV windings are designated by low-case letters a, b and c, and their finishes, by letters x, y and z.

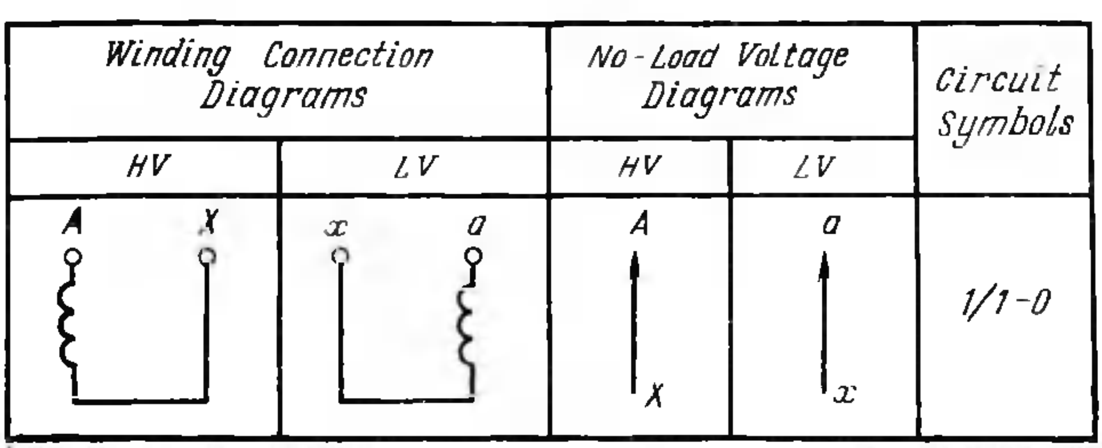
For three-winding transformers, the starts of the medium-voltage (MV) windings are designated by letters A_m, B_m and C_m, and their finishes, by letters X_m, Y_m and Z_m.

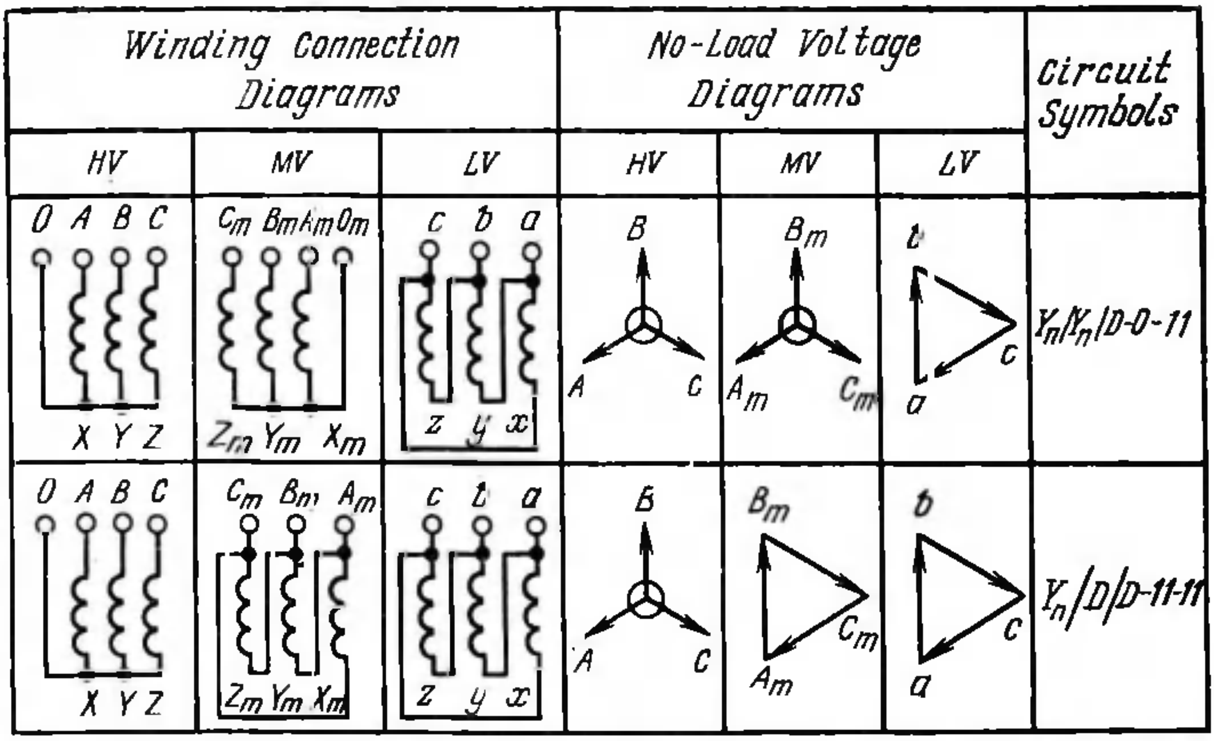
Where the neutral point (previously called the zero point), i.e., the common point of the three star-connected windings of a three-phase transformer, is made available for connection, it is designated 0 and 0_m on the HV and MV sides, respectively.

The winding terminals of single-phase transformers are designated in the same manner as those of the first phase in three-phase transformers, i.e., A-X, A_m-X_m and a-x.

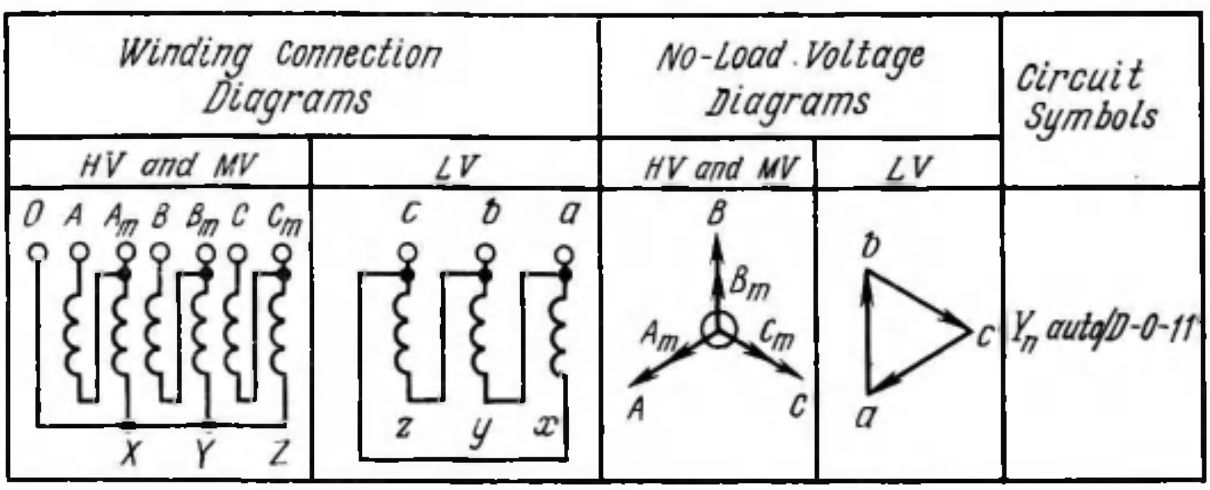
Three-phase transformer windings may be connected in a star, a delta, or a zig-zag (zig-zag or interconnected star).


Winding Connection Diagrams
No-Load Voltage Diagrams
Circuit Symbols
HV
LV
HV
LV
Y/Y$_n$-0
Y/D-11
Y$_n$/D-11
Y/Z$_n$-11
D/Y$_n$-11
D/D-0
(a)

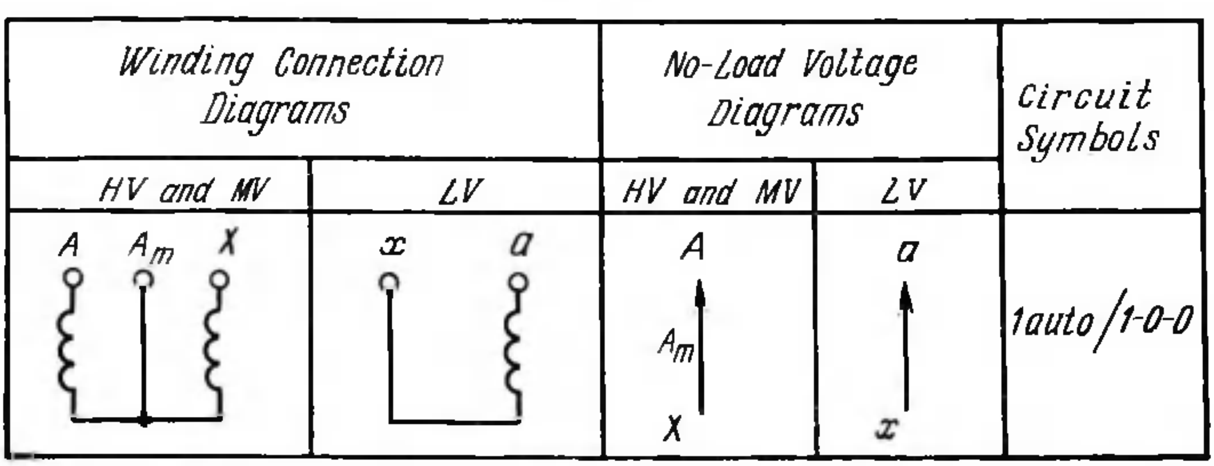

Winding Connection Diagrams
No-Load Voltage Diagrams
Circuit Symbols
HV
LV
HV
LV
1/1-0
(b)



(c)



(d)



(e)

Fig. 1.9. Winding connection diagrams for power transformers and autotransformers

(*a*) three-phase, two-winding transformers; (*b*) single-phase, two-winding transformers; (*c*) three-phase, three-winding transformers; (*d*) three-phase, three-winding autotransformers; (*e*) single-phase, three-winding autotransformers

These connections are respectively designated by special symbols, or by letters Y, D and Z. Where the neutral terminal is provided, subscript "n" is added to the letter designation (Y_n, Z_n).

According to the above Standard, the HV, MV and LV windings of transformers and autotransformers may have connections of the following types and phase-displacement groups:

1. Three-phase, two-winding transformers: Y/Y_n-0, Y/D-11, Y_n/D-11, Y/Z_n-11, D/Y_n-11 and D/D-0 (schematic winding connection and no-load voltage vector diagrams are shown in Fig. 1.9*a*).
2. Single-phase, two-winding transformers: 1/1-0 (Fig. 1.9*b*).
3. Three-phase, three-winding transformers: $Y_n/Y_n/D$-0-11 and $Y_n/D/D$-11-11 (Fig. 1.9*c*).
4. Three-phase, three-winding autotransformers: Y_n auto/D-0-11 (Fig. 1.9*d*).
5. Single-phase, three-winding autotransformers 1auto/1-0-0 (Fig. 1.9*e*).
6. Three-phase, two-winding autotransformers: $Y_n$auto.
7. Single-phase, two-winding autotransformers: 1auto.
8. Three-phase, two-winding, split-secondary transformers: Y_n/D-D-11-11, D/D-D-0-0.
9. Single-phase, two-winding, split-secondary transformers: 1/1-1-0-0.

As is seen in the figure, the windings in the star and delta connection diagrams are arranged not like a three-pointed star or a triangle, but in the same position as they are actually placed on the core limbs, i.e., vertically.

Figures 0 and 11 in the conventional designations mark the phase-displacement groups of winding connections. In the theory of alternating currents, sinusoidal, time-dependent electrical quantities (emf, voltage, current) are diagrammatically represented as vectors. A vector is drawn in the form of a line segment with an arrowhead. For example, when plotting a voltage vector, the arrowhead indicates the direction of the voltage and the length of the line segment represents the scaled peak (amplitude) value of the voltage during a period. A 30° angular displacement of the line voltage vector for the LV winding relative to the respective line voltage vector for the HV winding is adopted as a unit

for defining the phase-displacement groups of transformer winding connections. Phase displacement is counted off clockwise from the line voltage vector for the HV side. Thus, for example, phase-displacement group 0 means that there is no angular displacement between the line voltage vectors for the HV and LV windings, i.e. these vectors coincide; phase-displacement group 11 corresponds to a 330° (11 × 30°) angular displacement.

If we take the minute hand of a clock, set at 12 o'clock, to represent the line voltage vector for the HV winding, and the hour hand of the clock, the line voltage vector for the LV winding, phase-displacement group 0 will then correspond to twelve o'clock (the hands coincide), group 11, to eleven o'clock and so on (under the former standard, phase-displacement group 0 was numbered 12).

Which phase-displacement group will be obtained when connecting transformer windings into a circuit depends on the direction in which the windings are wound, on the connection sequence of the phase windings, and on the phase alteration in the case of a star or a delta connection. The winding direction is of special importance because it defines the direction of the emf's induced in the windings. For instance, if one and the same core limb carries two windings wound in the same direction, as is shown in Fig. 1.10*a*, the directions of the emf's induced in the windings will coincide, but if the windings are wound in opposite directions, the induced emf's will be in phase opposition (see Fig. 1.10*b*).

To avoid possible errors in connecting transformer windings, the latter are classed into left- and right-hand ones. A *left-hand* winding is one whose turns are wound counterclockwise (from the start of the winding viewed from the top) and a winding having its turns wound clockwise is a *right-hand* one.

One and the same type of winding connection may yield different phase-displacement groups. Figure 1.11 shows the phase-displacement groups obtainable with the Y/Y_n (star-star with neutral terminal) type of three-phase transformer winding connection. By using voltage vector diagrams, consider how some or other phase-displacement group can be obtained with this winding connection. The schematic diagrams of Fig. 1.11*a* and *b* present the HV and LV wind-

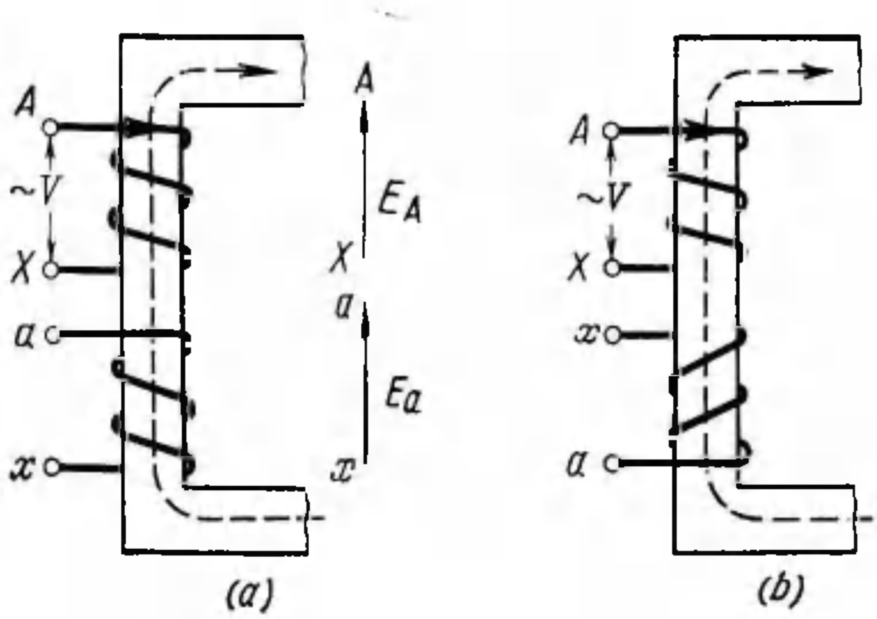


Fig. 1.10. Direction of induced emf's as dependent upon the hand of the windings

(*a*) left-hand windings (HV and LV): (*b*) left-hand winding (HV) and right-hand winding (LV)

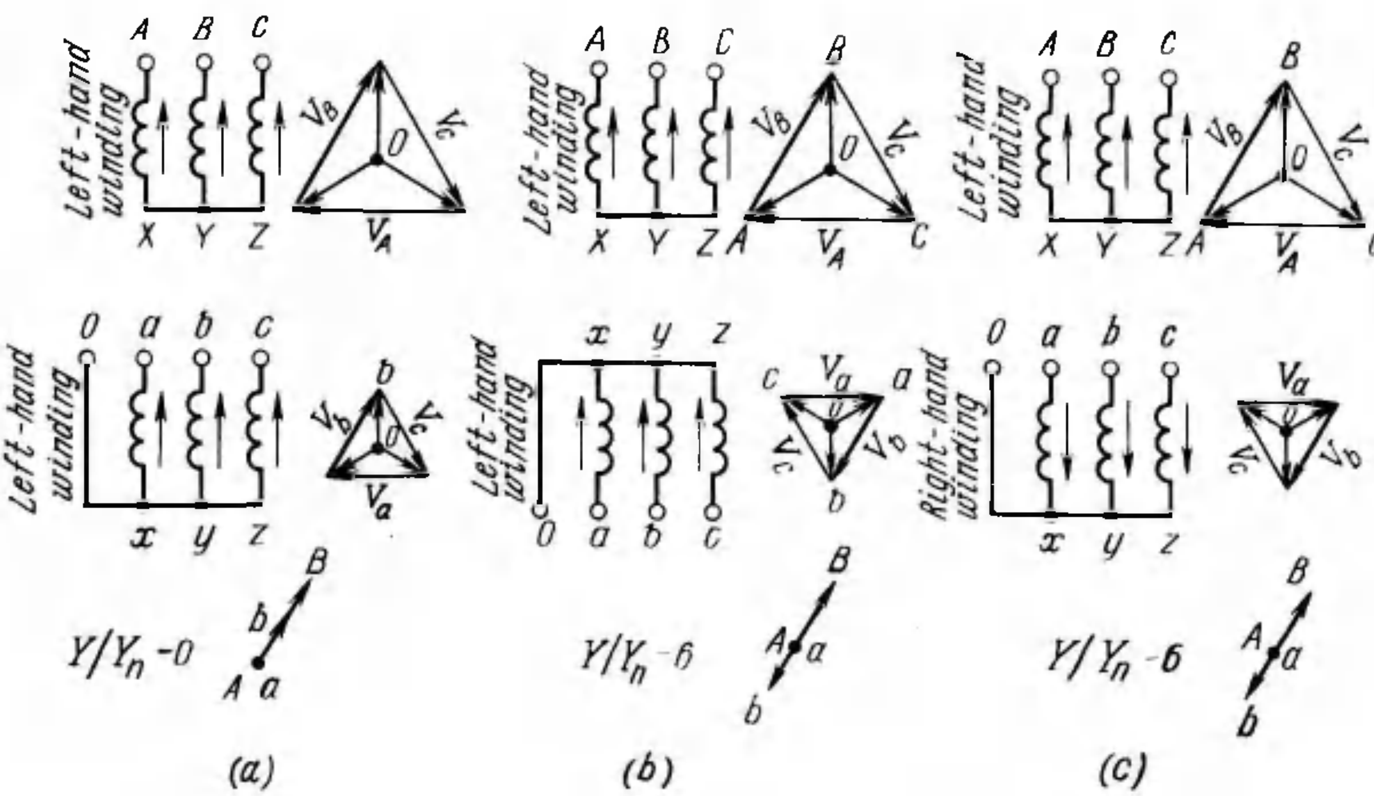


Fig. 1.11. Phase-displacement groups obtainable with the Y/Y_n (star-star with neutral terminal) type of three-phase transformer winding connection

(*a*) zero phase-displacement group (windings of the same hand); (*b*) 6th phase-displacement group (windings of the same hand, with the lead polarity of one of the windings being reversed); (*c*) 6th phase-displacement group (windings of opposite hands)

ings of the same (left) hand, and that of Fig. 1.11*c* shows the windings wound in opposite directions.

The phase voltages of the windings are determined by the difference in potential between their starts and finishes, or, which is the same, between the starts and the neutral point. On the vector diagrams, the phase voltages V_{AO}, V_{BO}, and V_{CO} are represented to a given scale by three vectors—*AO*, *BO*, and *CO*. They are drawn from the neutal point at an angle of 120° to one another, since in a symmetrical three-phase system of alternating currents, the emf's, currents and voltages are displaced in phase (time) by 120° $\left(\frac{2\pi}{3}\right)$ with respect to one another. The line (interphase) voltages are determined by the difference in potential between the starts of the respective phase windings, or, which is the same, by the vector difference of the phase voltages.

Having performed vector subtraction on the vector diagram of Fig. 1.11*a*, we obtain triangle *ABC*. Its sides—*AC*, *BA*, and *CB*—are the vectors of line voltages V_A, V_B, and V_C, respectively. The HV and LV phase windings shown in Fig. 1.11*a* are wound in the same direction, they are mounted on the like core limbs, and are likewise connected (in a star), therefore, obviously, the voltage vector diagrams for the HV and LV windings differ only in the size of the vectors (because of the different number of turns in the windings). If we superimpose the voltage vector diagrams for the HV and LV windings so as to make points *A* and *a* coincide, then, as is seen from the figure, the vectors of line voltages V_B and V_b will coincide in direction. By matching the other vertices of the triangles, one may satisfy oneself that the vectors of the like line voltages of the HV and LV windings have the same direction, i.e., they have zero angular displacement. Thus, this winding connection corresponds to the zero phase-displacement group and must be designated Y/Y_n-0.

Figure 1.11*b* shows a star-star winding connection diagram in which the starts of the LV windings are considered to be their finishes, and the finishes are considered to be the starts. In this case, the voltage vector diagram for the HV winding remains the same as before, whereas the direction of the voltage vectors for the LV windings will be reversed with

respect to their new starts and finishes. Now, after superimposing the voltage vector diagrams for the HV and LV windings, we shall see that the vectors of the like voltages have opposite directions. Such a winding connection corresponds to the nonstandard 6th phase-displacement group and is designated Y/Y_n-6. In this way, we have ascertained that if the polarity of the leads in either the HV or LV windings in a star-star connection is reversed (the lead markings are changed), the phase-displacement group will change from the zero to the sixth (or vice versa).

The winding connection diagram shown in Fig. 1.11*c* differs from the previously analysed diagrams in that the HV windings here are the left-hand ones, whereas the LV windings are of the right-hand type. Therefore the direction of the induced emf's and voltages of the LV windings is reversed. Hence all the vectors in the vector diagram for the LV windings are opposite to those of the HV windings. This diagram repeats the one in the previous case (see Fig. 1.11*b*), and the winding connection corresponds to the sixth group.

Thus, we have ascertained that the reversal of the direction of transformer windings is equivalent to the change of their starts and finishes and results in a different phase-displacement group.

Figure 1.12 illustrates how some phase-displacement groups can be obtained with a star-delta connection of transformer windings wound in the same direction. In both cases (Fig. 1.12*a* and *b*), the HV windings are connected likewise, therefore their voltage vector diagrams (shown to the right of the windings) are the same. In the first case (Fig. 1.12*a*), the delta connection of the LV windings follows the standard sequence—*a-y*, *b-z* and *c-x*. The superposition of the voltage vector diagrams constructed for this type of winding connection shows that it corresponds to the eleventh group (Y/D-11) In the second case (Fig. 1.12*b*), the LV windings have their start and finish lead markings changed, and, although the windings here are connected in the sequence *a-y*, *b-z*, and *c-x*, as is shown in the figure, the line voltage vectors are turned clockwise through 180° with respect to those of the previous diagram. The winding connection thus obtained corresponds to the fifth group (Y/D-5).

The former standard made provision for the fifth phase-

displacement group, and, at present, many transformers in actual service in this and other countries belong to this group. To reconnect transformer windings from the 5th to the 11th group, one has to change the sequence of the delta-connected windings and change at the same time the markings of their start and finish leads, i.e., to consider the

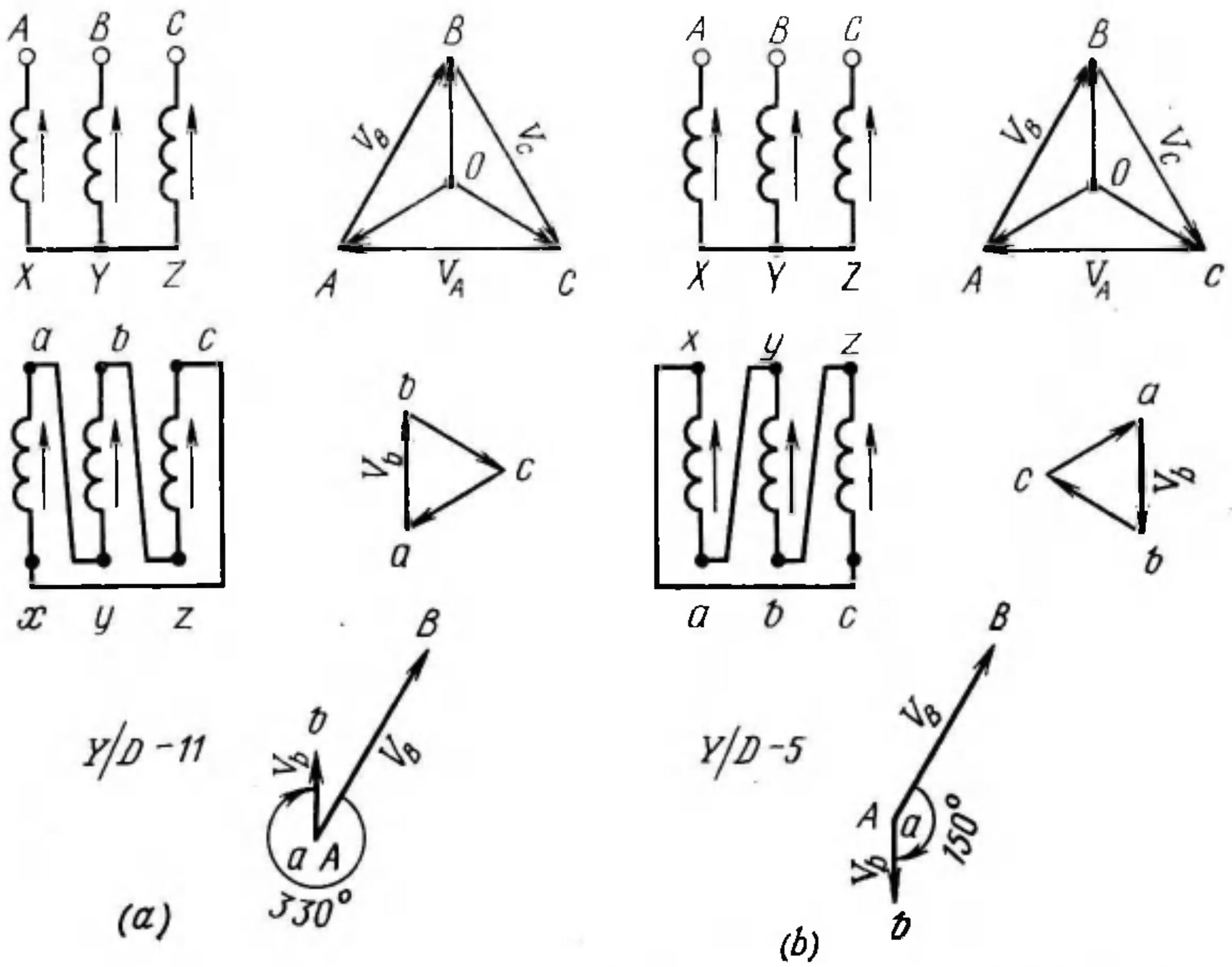


Fig. 1.12. Some phase-displacement groups obtainable with a star-delta connection of transformer windings of the same hand

(*a*) 11th phase-displacement group; (*b*) 5th phase-displacement group (reversed lead polarity of the LV winding with changed delta-connection sequence)

winding finishes to be their starts and connect the line conductors to them, while making the starts be the finishes. In other words, one has to change from the diagram shown in Fig. 1.12*b* to that of Fig. 1.12*a*.

By constructing similar vector diagrams, it can be shown that if the LV windings of Fig. 1.12*a* are connected delta in the sequence *a-z*, *b-x*, and *c-y* (without changing the lead polarity), the connection will correspond to the nonstandard first group (*Y*/*D*-1).

Using various combinations of winding direction, phase alteration, winding connection sequence, and lead polarity enables one to obtain twelve phase-displacement groups with the *Y/Y* and *Y/D* winding connections. To avoid errors, special attention is given to the winding connection diagrams and phase-displacement groups of transformers.

The identity of the phase-displacement groups is one of the chief prerequisites for the parallel operation of transformers. Making transformers of different phase-displacement groups operate in parallel is impermissible in view of the heavy circulating currents resulting therefrom.

1.6. Autotransformers

The primary and secondary windings of transformers are not connected electrically, and there is only magnetic linkage between them. On the contrary, the HV and LV windings of autotransformers are connected electrically so as to from a single continuous winding, a portion of which is common to both the primary and secondary circuits. Fig. 1.13 presents a schematic diagram of a single-phase step-down autotransformer supplying a load. Under conditions of no load, the operation of the autotransformer does not differ from that of the ordinary transformer. The applied voltage V_1 is uniformly distributed among the turns of winding Ax carrying the no-load current, hence the voltage per turn is the same throughout the winding and the secondary voltage V_2 is proportional to the number of turns in the common winding ax:

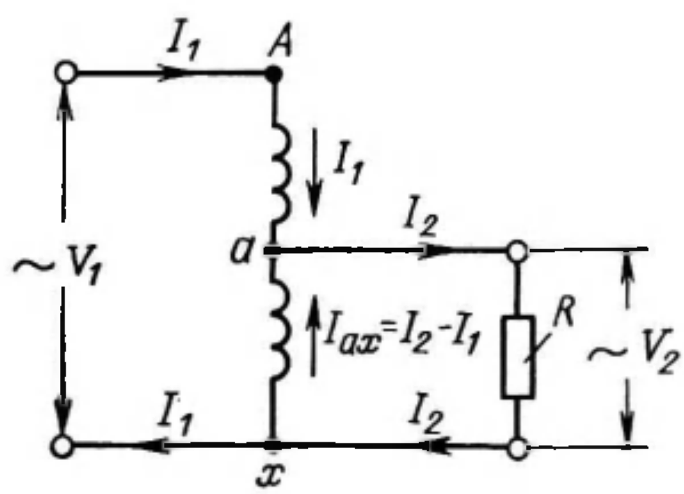


Fig. 1.13. Schematic diagram of a loaded single-phase step-down autotransformer

$$V_2 = V_{ax}$$

The transformation ratio of the autotransformer is

$$k = \frac{V_1}{V_2} = \frac{V_{Ax}}{V_{ax}}$$

Consider the operation of a loaded autotransformer, assuming that the no-load current is zero. It can be seen from the figure that current I_1 flows on the primary side, while the secondary side (the load circuit) carries current I_2, I_2 being $> I_1$ since $V_2 < V_1$. Therefore, current I_{ax} flowing through the common winding ax is equal to the difference between currents I_2 and I_1:

$$I_{ax} = I_2 - I_1$$

or

$$I_2 = I_1 + I_{ax}$$

Thus, the secondary current I_2 consists of two components—the primary current I_1 which flows through the series winding Aa, by-passing the common winding ax, and current I_{ax} flowing through the common winding ax and equal to $I_2—I_1$. Correspondingly, the secondary power S_2 also consists of two components—the conductive kV A which is directly transferred from the primary to the secondary circuit through the series winding Aa, and the electromagnetic kV A which is transferred to the secondary circuit by transformer action, i.e., by electromagnetic induction:

$$S_2 = S_{cond} + S_{em}$$

It follows from the foregoing that the secondary (common) winding of the autotransformer is calculated for the difference of currents $I_2—I_1$, rather than for the secodary current I_2, while the primary (series) winding is calculated for the difference of voltages $V_1—V_2$, and it is this fact that explains the economic advantage of autotransformers. The autotransformer is characterized by the *load* kV A, or *circuit power*, $S = V_1 I_1$, which is indicated on the rating plate, and by the *equivalent* kV A, or *design power*, $S_{eq} \approx V_2(I_2—I_1)$. The ratio of the equivalent kV A to the load kV A is termed the *auto fraction*, or the *co-ratio* of the autotransformer:

$$\alpha = \frac{S_{eq}}{S}$$

Substituting into the above formula the expressions for S_{eq} and S in terms of voltages and currents and carrying out

the necessary transformations, we get

$$\alpha = 1 - \frac{1}{k}$$

where k is the transformation ratio of the autotransformer.

Expressing the equivalent kV A in terms of α and S yields

$$S_{eq} = \alpha S = \left(1 - \frac{1}{k}\right) S$$

From the above equation it follows that the equivalent kVA is by a factor of α less than the load kV A, the values of α being most advantageous with the ratio of transformation approaching unity.

The example below illustrates the advantages of the autotransformer over the ordinary transformer.

Example. A power of 120 MV A is to be transferred from a line with a voltage of 220 kV to another line with a voltage of 110 kV. Determine the equivalent kV A of the autotransformer required to do the job.

Solution. The ratio of transformation is

$$k = \frac{220}{110} = 2$$

The auto fraction

$$\alpha = 1 - \frac{1}{2} = 0.5$$

The equivalent kV A

$$S_{eq} = 120 \times 0.5 = 60 \text{ MV A}$$

As is seen from the above example, only half of the power will be transferred to the 110-kV line by transformer action, and, although the load to be delivered is 120 MV A, the autotransformer can be calculated for 60 MV A, which is its design power. If an ordinary transformer had to be used for the purpose, it must have been calculated for 120 MV A.

Thus, compared with the ordinary double-wound transformer, the autotransformer has the advantage of smaller mass, size, and consumption of active materials (core steel and winding copper), lower core and copper losses, and hence, higher efficiency.

Single-phase autotransformers operating in three-phase groups, as well as three-phase autotransformers, are built for high capacities and voltages. Such transformers are widely

used for interconnecting power transmission lines with different rated voltages, for example, 110 and 220 kV, 220 and 500 kV. Autotransformers of comparatively low capacities and voltages are employed for starting large A. C. motors. Autotransformers gain particular importance in view of the growth of the unit capacities of power transformers, because the capacity of an autotransformer is much higher than that of an ordinary double-wound transformer of the same overall size.

However, from the expressions for the equivalent kV A and auto fraction, it is clear that the use of autotransformers is economically advantageous, provided the transformation ratio is not very high (not more than four). With too high a transformation ratio, the auto fraction approaches unity, and this means that the equivalent kV A of the autotransformer reaches the kV A of the equivalent double-wound transformer. Besides, in the autotransformer, the circuits with different voltages (the HV and LV circuits) have a common electrical connection and consequently, the insulation of the LV winding must be as heavy as that of the HV winding. Also, the reactance of the autotransformer is lower than that of the double-wound transformer for the same duty and, as a result, its inherent ability to protect itself from excessive short-circuit currents is much poorer. Because of this, special devices have to be used to limit these currents to a safe value. The disadvantages mentioned above restrict the application of autotransformers.

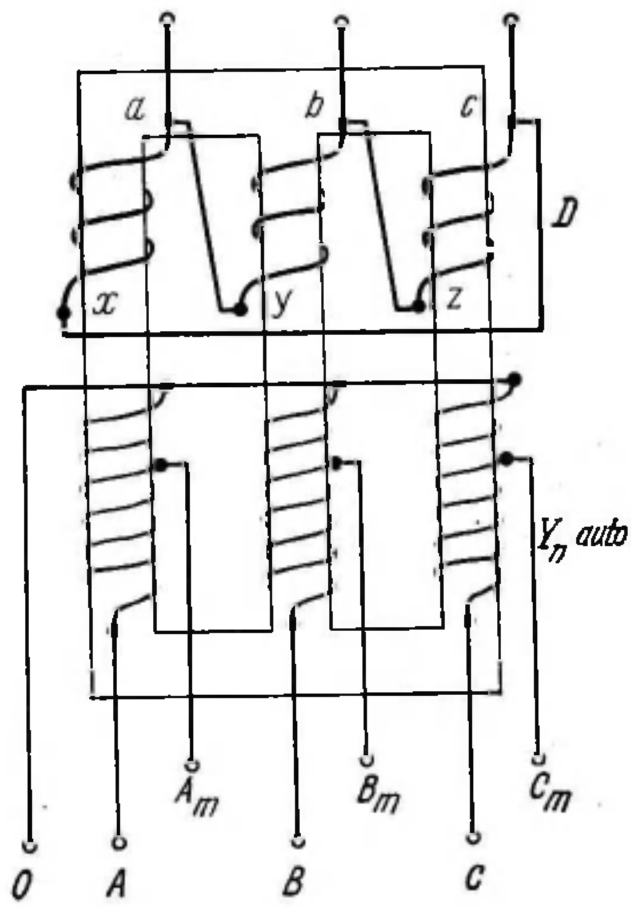


Fig. 1.14. Schematic diagram of a three-phase, three-winding autotransformer (the LV winding is delta-connected, while the HV and MV windings are auto-connected, with the neutral point being brought out)

Large autotransformers are predominantly built as three-winding units in which one of the windings (usually the LV

one) is electromagnetically linked with the other two windings (MV and HV) which are auto-connected, as is shown schematically in Fig. 1.14.

1.7. Specific Features of Some Special-Purpose Transformers

Rectifier Transformers

A number of industries use D.C. power for some applications, such as electric traction in transportation, electrolytic plants for the production of aluminium, copper, zinc, chlorine and hydrogen gases and other substances in nonferrous metallurgy and electrochemical industry, vacuum arc furnaces for smelting special steels, D.C. motor drives, and the like. The direct current required for such applications is obtained by rectifying alternating current.

Until recently, this purpose was served mainly by ionic (mercury-arc) rectifiers which depend for their operation on the valve action of electric arc. Lately, thanks to the rapid development of semiconductor technology, wide application have found germanium and silicon rectifiers, both noncontrolled—diodes, and controlled—thyristors. Semiconductor rectifiers make it possible to built perfect converter installations of comparatively small size and mass, which have very good electrical characteristics and are simple in design and easy in maintenance.

The transformers intended for supplying A.C. power for rectifier installations are referred to as *rectifier transformers*; together with rectifier elements they constitute rectifier units. The operation of rectifier transformers is peculiar in that their primary winding is supplied with A. C. power at mains frequency, while the secondary is connected into a circuit containing rectifying elements which conduct current in one direction only.

High-power rectifier units work from a three-phase supply. The primaries of the three-phase rectifier transformers are usually connected in a star, and their secondaries, in a star, a double star, a zigzag, or a double zigzag. Accordingly, a three- or a six-phase system is obtained on the secondary side.

During operation, the secondaries of rectifier transformers alternately carry unidirectional (direct) currents, and with an ill-chosen winding connection, this gives rise to a unidirectional magnetic flux superimposed on the main flux in the transformer core limbs, unless some additional devices are provided in the rectifier circuit to prevent it. This additional flux tends to oversaturate the core and is termed the *D.C. saturating flux.* Flowing through all the three core limbs simultaneously, and then from yoke to yoke and through air and tank walls, the saturating flux causes additional losses and the local overheating of individual transformer components, and disturbs the symmetrical distribution of magnetizing forces. Therefore, when designing rectifier units, one tries to select a rectifier circuit arrangement ensuring a minimum unbalance of the magnetizing forces, a maximum symmetry of their distribution among the phases, and a minimum ripple in the rectified current and voltage.

A circuit arrangement most suitable for high-power rectifier units is a six-phase system with an interphase transformer, sometimes called an absorption-reactance coil, which is shown in Fig. 1.15*a*. The three-phase system on the primary side is converted into the six-phase one on the secondary side by making the secondary phase windings in the form of two separate windings wound in opposite directions (right- and left-hand), or of two windings of the same hand, one of them having its lead polarity reversed. The phase windings are connected in stars *2* and *4*, the star points 0_1 and 0_2 being connected into common neutral 0 through an interphase transformer *IPT*. In this way, a six-phase circuit is obtained on the secondary side.

The vector diagram of the phase emf's is illustrated in Fig. 1.15*b*. With this arrangement, the D.C. saturating flux is excluded altogether. The mid-point 0 of the interphase transformer is the negative terminal of the load circuit. The inductive reactance of the transformer is high, so it limits current between points 0_1 and 0_2 (see Fig. 1.15*a*). On the other hand, the reactance of each half of the interphase transformer winding, 0-0_1 and 0-0_2, is low enough, because their respective magnetic fluxes are opposite to each other and cancel out almost completely.

The interphase transformer has the effect of spreading the duration of the operation ("burning") of each rectifier anode to one-third of a period, and at any instant one anode of one set and one of the other set are in parallel operation. This causes the load current to divide equally between the two star-connected secondaries, so that the output voltage is the mean of the respective phase voltages. This connection is

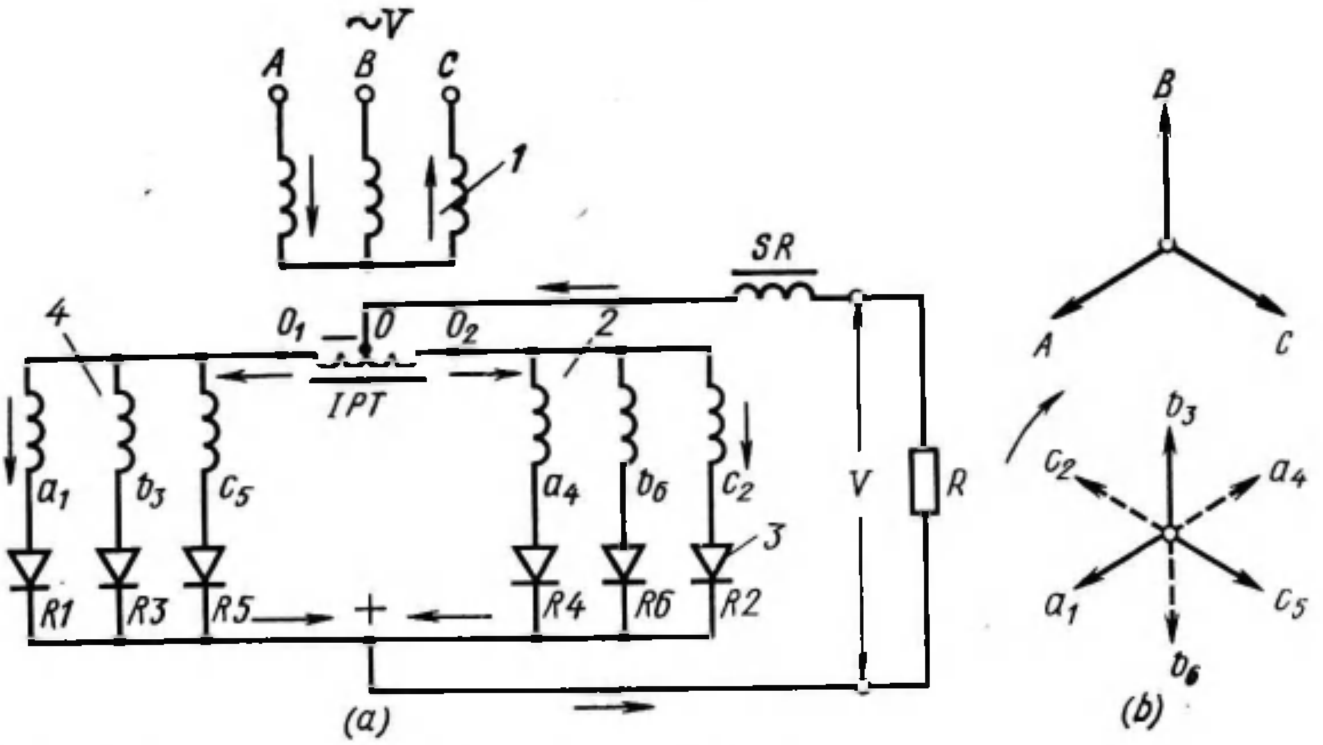


Fig. 1.15. Six-phase rectifier circuit with an interphase transformer

(*a*) winding connection diagram (star-double inverted star, Y/Y_n-Y_n-0-6) with interphase transformer, *IPT*, and rectifiers, *R*1 through *R6*: (*b*) vector diagram of phase emf's (solid lines show the emf's of the direct star, and dash lines, those of the inverted star); *1*—direct star of the primary winding; *2* and *4*—inverted stars of the secondary winding; *3*—rectifier; *SR*—smoothing reactor; *R*—D.C. load

therefore sometimes called a "double three-phase" rather than a six-phase circuit. Since now two secondary windings placed on different transformer core limbs operate simultaneously, the magnetizing forces of the primary and secondary windings are equalized.

Figure 1.15*a* illustrates an instant when the first and the second rectifier anodes of phases a_1 and c_2 are in operation. As is seen from the figure, the like phase currents on the primary and secondary sides are equalized, and so are the magnetizing forces produced by them.

Every one-third of a period, when the voltage of the next phase becomes higher than that of the previous phase, in

each of the star-connected secondary circuits there takes place the transfer of current from one rectifier anode to another. Once the interphase transformer is removed from this circuit and the star points of the secondary windings are connected together, a D.C. saturating flux varying at a frequency of three times the supply frequency, sets in in

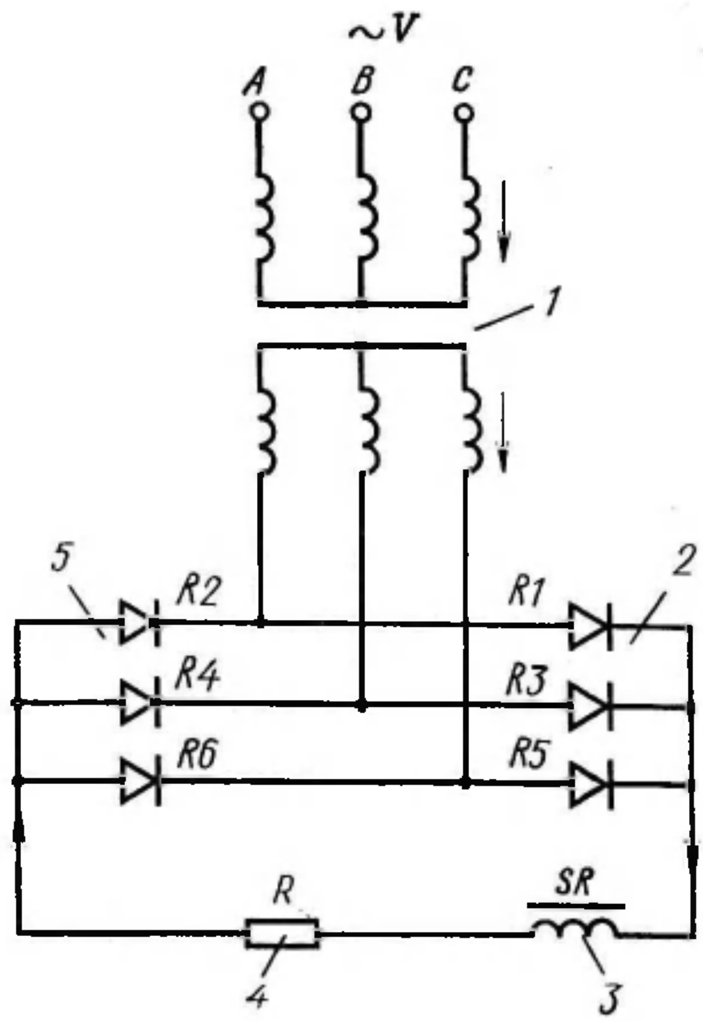


Fig. 1.16. Bridge (full-wave) rectifier circuit

1—three-phase rectifier transformer (star-star winding connection); *2*—first rectifier (diode) group; *3*—smoothing reactor; *4*—load; *5*—second rectifier (diode) group

the core limbs of the rectifier transformer, this giving rise to a substantial emf which augments the reactive voltage drop and sharply deteriorates the operation of the rectifier unit. For this reason, the six-phase rectifier circuit without an interphase transformer (the diametrical six-phase connection) is used but seldom. Where such circuits are employed, the primary winding of the rectifier transformer is connected delta.

Three-phase bridge (full-wave) rectifier circuits (Fig. 1.16) have found wide application. In such a circuit, the secondary winding of the rectifier transformer supplies phasewise three parallel-connected circuits, each containing two rectifier elements. To reduce ripple in the rectified voltage and

current, a smoothing reactor *SR* is included in the load circuit (resistor *4*). This circuit arrangement prevents the development of the D.C. saturating flux. At any instant there are two rectifier elements operating simultaneously, and the rectified voltage undulates at a frequency of six times the supply frequency (in this respect the circuit is equivalent to the diametrical six-phase half-wave).

Six-phase connections are used in rectifier units with a capacity in excess of 250 kW; rectifier units with capacities over 4 000 kW employ twelve-phase connections.

Zigzag connections of the rectifier transformer secondaries also prevent the D.C. saturating flux, but such connections require that tne transformer have a higher equivalent kVA, hence the need for extra active materials.

Better results are obtained with a star-double-zigzag connection. Such a connection ensures the balance of magnetizing forces in the transformer core, for with any of the rectifier elements in operation, current flows through the two halves of the associated branch winding of the transformer secondary, which are placed on different core limbs. Therefore, the primary and secondary windings on any core limb are loaded symmetrically.

When selecting winding connections and phase-displacement groups for rectifier transformers, one should refer to the pertinent standard (USSR Standard 16772—75). The type designations of transformers for application in conjunction with mercury arc rectifiers contain the letter P; for example, the type designation "TMPУ" should be read as follows: a three-phase (T), oil-natural-cooled (M) transformer for mercury-arc (P) rectifiers with an interphase transformer (У). The designations of transformers intended for use with semiconductor rectifiers include the letter П, for instance, ТМПУ.

Rectifier transformers may be oil-immersed and dry-type and are built with both on- and off-load (off-circuit) voltage-control arrangements. Depending on the application field of rectifier units, their capacity ranges from a few kilovolt-amperes to 100 000 kilovolt-amperes, current, from tens to 200 000 amperes, and voltage, from 0.380 to 220 kilovolts on the primary side and from 6 volts to a few kilovolts on the secondary (rectifier) side.

As distinct from power transformers, rectifier transformers have their LV windings placed over the primary (input-circuit) windings which are placed next to the core limbs. This permits a large number of parallel circuits and leads made of thick bars of solid copper to be arranged in immediate proximity to the windings and provides for better cooling conditions.

The KB-200 type silicon diodes and the TB-200 and TB-500 type thyristors, capable of handling currents of up to 200 and 500 A, respectively, at voltages of 220-380 V, are widely used as power rectifier elements in rectifier units. To obtain heavy currents at the desired voltages, the diodes and thyristors are connected in series and parallel to form individual blocks which are frequently installed together with the core-coil unit in the transformer tank filled with transformer oil.

Arc-Furnace Transformers

The melting of steel and other metals in arc furnaces is effected by single- or three-phase current at low voltage. Metal is melted by the heat of the arc maintained between the tip of a graphite electrode (three such electrodes are used in three-phase furnaces) and the metal charge (bath after the molten state is reached) in a furnace, the arc being supplied with current from the secondary winding of the furnace transformer. The capacity of arc-furnace transformers often amounts to many thousand kilovolt-amperes, and as the secondary voltages of such transformers are merely 74 to 200 volts, their secondary currents reach tens and hundreds of thousands of amperes.

Arc-furnace transformers are distinguished for a small number (one or two) of the secondary turns of a large cross-sectional area. Because of considerable variation in arc-furnace service, the secondary voltage of furnace transformers, as distinct from power transformers, has to be controlled over a very broad range, sometimes extending to $\pm 50\%$. This is done by changing voltage-control taps in the primary winding connected in a delta. The voltage range provided by the tapped primary is extended by changing the connections of the primary windings from delta to star.

The load on arc-furnace transformers sharply changes covering the range from no load to short circuit. Under short-circuit conditions, enormous mechanical stresses develop in the transformer windings and leads made up of a large number of solid copper bars, so to make them sufficiently strong, they must be reliably fastened and intensively cooled. To limit short-circuit currents, the short-circuit voltage $v_{sh\text{-}c}$ is increased, or a supplemental reactance (reactor) is included in the primary circuit. In contrast to power transformers, the LV windings of arc-furnace transformers are placed over the HV ones.

Arc-Welding Transformers

There are many types of arc-welding transformers, which differ in capacity and design but have the same purpose—to supply 50-hertz single-phase current to the arc used in the manual or machine (automatic) welding, cutting, and surfacing of metals.

A welding transformer set converts a 220- or 380-volt supply into power at 60 to 65 volts, which is required for the arc-welding process, and incorporates means of adjustment whereby the welding current can be varied continuously within suitable limits. Welding transformer sets are usually made dry-type, and consist of the transformer proper (core, windings) and a variable reactor (choke) to control the secondary current of the transformer. Auxiliary equipment includes an ammeter, terminal boards to connect the primary winding to the supply mains and the secondary, to the welding circuit, and a capacitive filter to bar the radio interference produced by the transformer during welding.

Welding transformer sets are put out both in the form of integrated units with the transformer and reactor placed in a common shell (monocarcase or one-body welding sets) and as sets made up of transformers and reactors encased individually (two-body welding sets). In the former case, the transformer and reactor windings are placed on a common core. Fig. 1.17 illustrates schematically the circuit arrangement and operation of a two-body welding set. In this figure, *WT* stands for welding transformer and *R*, for reactor. The welding current is varied by changing the air

gap in the reactor core. As the gap is reduced, the reactance in the welding circuit is increased, this bringing down the current, and vice versa.

More often than not, welding transformers are designed as single-phase units; they may have different characteristics

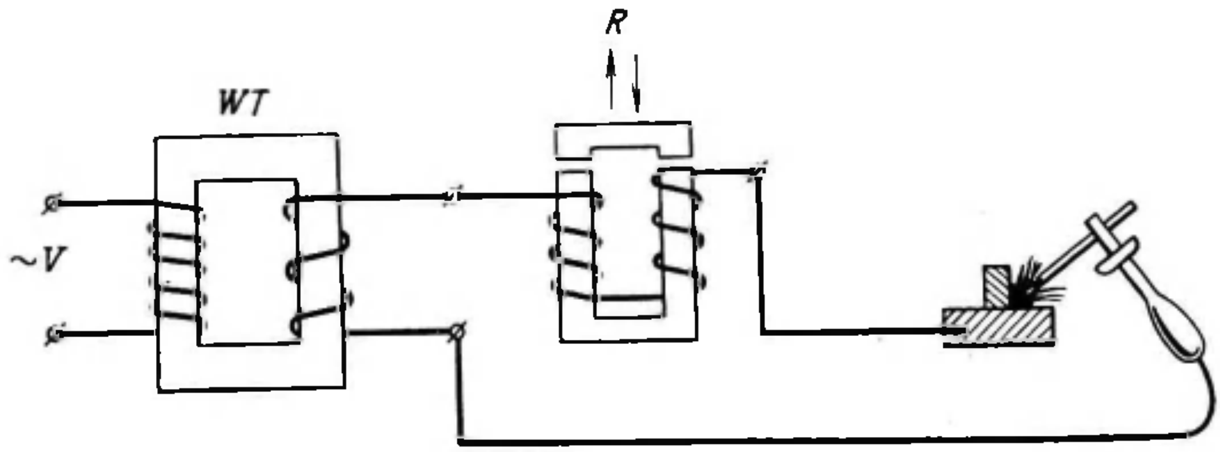


Fig. 1.17. Elementary diagram of a welding transformer

and technical specifications and merit a special consideration, but this lies outside the scope of this book.

Instrument Transformers

Modern electrical installations handle voltages as high as 750 kilovolts and even higher, the currents involved reaching tens of kiloamperes and more. To measure such values directly would require enormously bulky and expensive measuring instruments. In some cases, such measurements would be entirely impossible. Moreover, the use of instruments connected directly to a high-voltage circuit would expose operators to electric shock hazards. Instrument transformers extend the measurement range of ordinary electrical measuring instruments and, at the same time, isolate them from high-voltage circuits.

Instrument transformers are used in conjunction with ammeters, voltmeters, power meters, protective relaying and automatic control devices, recording wattmeters for registering the amount of generated and consumed power, and so on.

Current Transformers. Like any other type of transformer, the current transformer has a core and two windings—primary and secondary. It changes a heavy current in a power

circuit to a value suitable for measurement with an ordinary ammeter. As a rule, current transformers are designed to have such a transformation ratio as would provide a standard 5- or 1-ampere current on the secondary (instrument) side when full rated current is flowing in the primary winding.

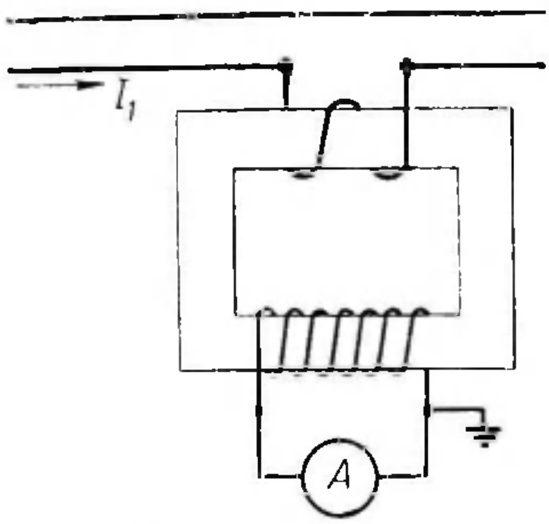


Fig. 1.18. Measuring current with a current transformer

The primary winding of the current transformer is connected in series with the power circuit, so to reduce the loss of power in, and the voltage drop across, the winding, the latter is made to have a single or a few turns of a heavy-gauge wire (see Fig. 1.18). The secondary winding consists of a large number of turns of comparatively fine wire, and its ends are connected directly to an ammeter, or to the current circuits of other instruments.

Given the secondary current, I_2, and the transformation ratio, k_c, of the current transformer, the primary current can be found to be

$$I_1 = k_c I_2$$

Panel-mounted instruments, i.e., those connected permanently, have their scales calibrated to read directly current values corrected for the transformation ratio of the associated current transformers.

Figure 1.19 illustrates the use of a current transformer in a split-electromagnet (hook-on) ammeter which is a portable current-measuring instrument. A cable or busbar *4* through which flows the current to be measured constitutes the single-turn primary winding of the transformer. The secondary winding *3* is wound around a split core *5* made in the form of tongs which can be opened and closed by pressing and releasing a handle *1*. Ammeter *2* is connected across the secondary winding. To measure the current, one needs only to encircle the cable by the tongs.

It is not allowed to open the secondary circuit of the current transformer when current is flowing through its primary circuit, because this brings about, in the first

place, heavy overvoltages across the secondary winding, which are dangerous to the instrument itself, as well as to the operators, and secondly, an increase in the resultant magnetic flux in the core, since there is no demagnetizing effect of the secondary mmf, causing an increase in the core induction and, as a result, the overheating of the core and eventual failure of the transformer. When it is desired to

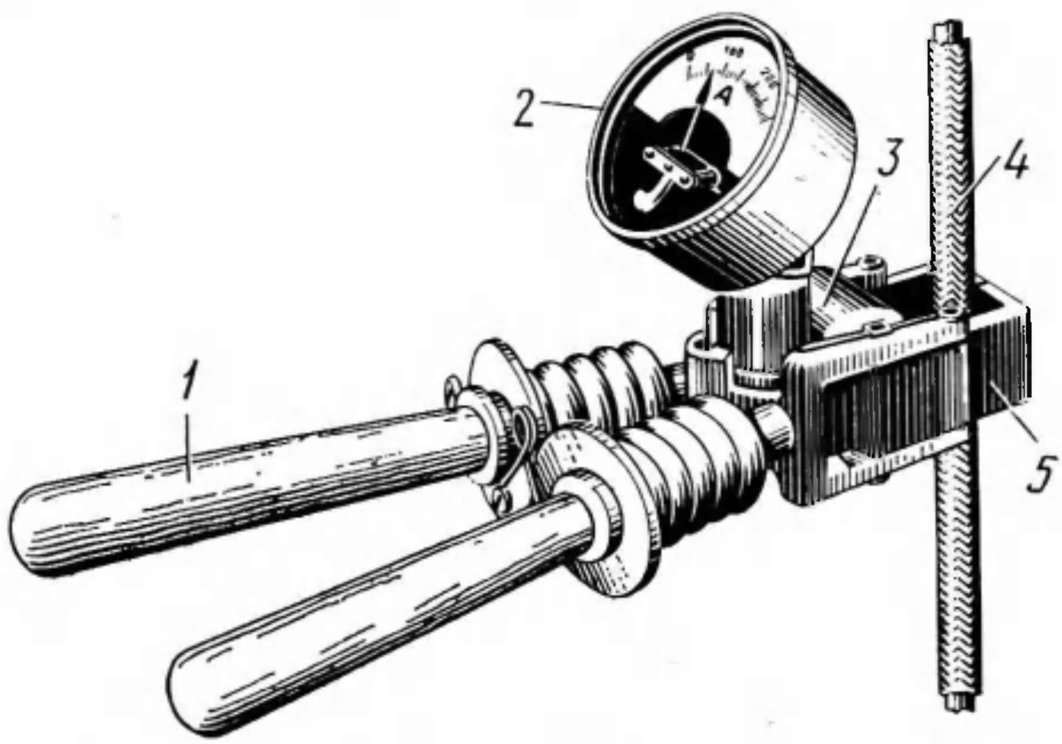


Fig. 1.19. Split-electromagnet (hook-on) ammeter

1—handle; *2*—ammeter; *3*—secondary winding; *4*—cable (busbar); *5*—core

disconnect the ammeter, the secondary winding is to be shunted by a jumper wire in order to avoid the opening of the secondary circuit. For the sake of safety in case of an insulation breakdown between the primary and secondary windings, the secondary winding is connected to the transformer body and earthed.

Voltage transformers. These transformers are used primarily for lowering voltages in electrical installations to values which render them convenient for measurement. In accordance with the pertinent USSR Standard, all voltage transformers have their secondaries wound for 100 volts. The primary voltage is determined by multiplying the measured secondary voltage by the transformation ratio of the voltage transformer:

$$V_1 = k_v V_2$$

According to their accuracy, voltage transformers, as well as current transformers, are divided into the following classes: 0.2, 0.5, 1, and 3. Voltage transformers rated at up to 0.66 kV are dry-type and those for 3 kV and higher are oil-insulated. There are also epoxy-encapsulated voltage transformers for 3-35 kV.

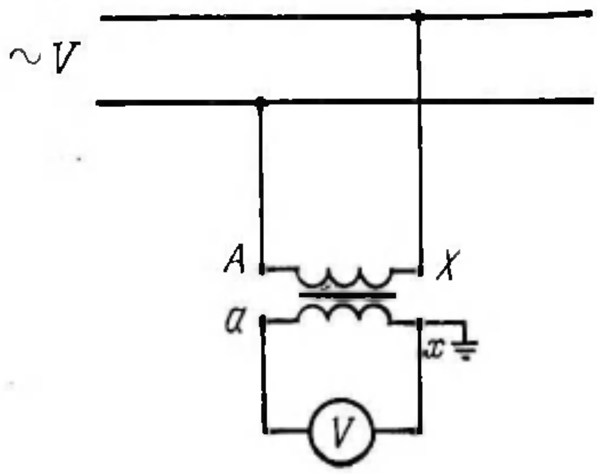


Fig. 1.20. Measuring voltage with a voltage transformer

Figure 1.20 shows a voltage-measuring circuit using a voltage transformer. For the sake of safety, the secondary windings and bodies of voltage transformers are earthed.

Voltage transformers may be single- or three-phase type. Like current transformers, they may differ in design and construction.

1.8. Operation of Power Transformers Under Actual Service Conditions

To ensure reliable and economical operation, transformers must meet the following requirements:

satisfy the conditions of parallel operation;

maintain temperature rise within specified limits;

withstand overvoltages within specified limits;

withstand external short-circuiting at the specified overcurrent ratio (maximum to rated current ratio) and current duration;

provide for voltage control.

Parallel Operation of Transformers

Most power transformers do not operate independently, but in parallel with one another. Transformers are said to be operating in parallel when the like leads of their primary and secondary windings are connected to the like conductors of a common line. The parallel operation of two three-phase, two-winding transformers is illustrated schematically in Fig. 1.21*a*. Figure 1.21*b* is a single-line diagram

where all the three phases are conventionally shown as a single line, which considerably simplifies the diagram and makes it more clear. In such diagrams, two-winding transformers are symbolized by two circles and three-winding ones, by three circles.

The parallel operation of transformers is more economical than individual operation and provides for some power

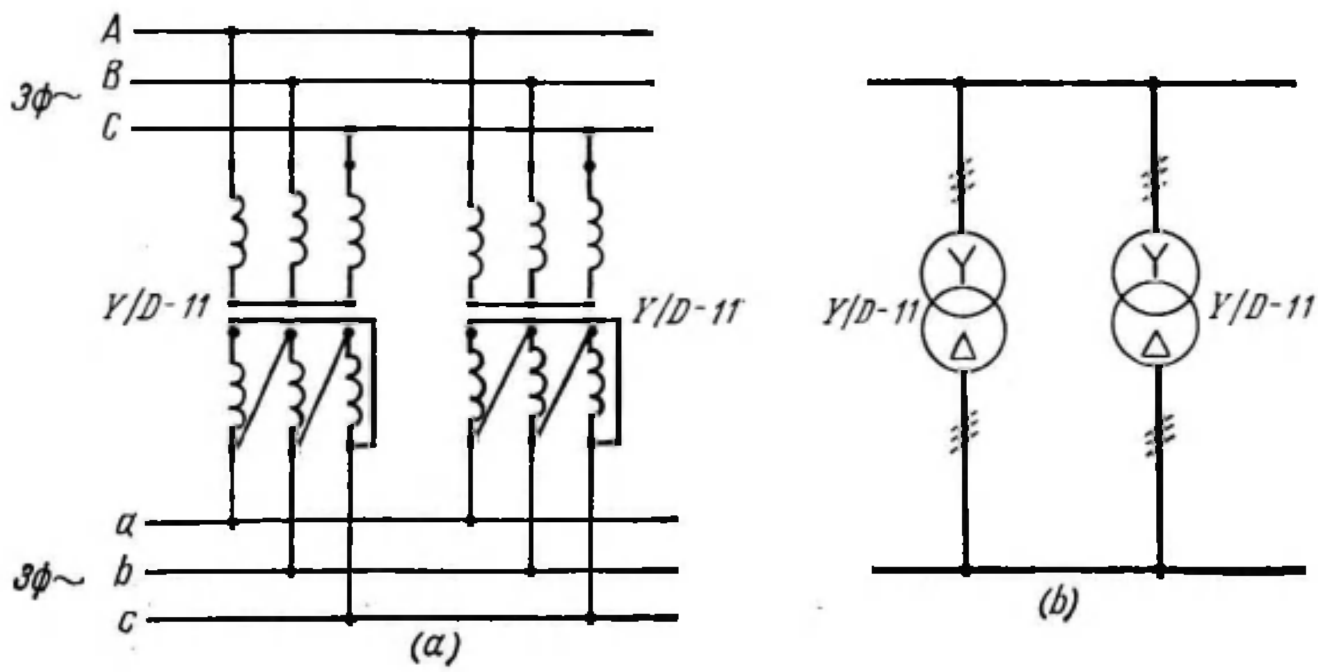


Fig. 1.21. Illustrating parallel operation of two three-phase, two-winding transformers

(a) three-line diagram; (b) single-line diagram

reserve. To ensure the possibility of operating in parallel, transformers must meet a number of technical requirements among which the chief are the following:

equality of the primary and secondary voltages and consequently, of the transformation ratios;

equality of short-circuit (impedance) voltages;

identity of phase-displacement groups of winding connections.

Heating of Transformers

The electrical energy lost in a transformer in operation is dissipated as heat in the windings, the core, and the structural and other parts of the transformer. As a result, the transformer is heated up. A rise in the temperature of the

transformer and of its individual parts above the maximum safe value causes a sharp reduction in the service life of the transformer, and in some cases, results in its failure.

Among the insulating materials used in transformers, cable paper is one of the least heat-resistant. The maximum temperature that cable paper immersed in oil can withstand for prolonged periods without any material deterioration of its insulating properties is 105°C. According to its thermal stability, cable paper belongs to Class A insulation.

A rise in transformer oil temperature above 95°C causes an intensive ageing (oxidation) of the oil, resulting in the deterioration of its heat-conducting and insulating properties.

To ensure that transformers may operate reliably throughout their normal service life (25 years on the average), USSR Standard 11677—75 specifies for various transformer parts the following maximum values of their temperature rise over the ambient:

Windings	65°C
Core (on the surface) and structural components	75°C
Top oil:	
if protected from air (transformers with conservators, inert gas cushions or blankets, hermetically sealed tanks, or with other means of protection whereby oil can be prevented from contacting air)	60°C
in other cases	55°C

In dry-type transformers using insulation of Classes A, E, B, F, and H, the winding rise over the ambient must not exceed 60, 75, 80, 100, and 125°C, respectively.

The above maximum temperature rise values are specified on condition that the ambient air temperature should not exceed 40°C. If the cooling medium is water, its temperature at the input to the transformer cooler should not exceed 25°C. On the basis of the maximum permissible temperature rise values, the design maximum temperatures for the windings and the core (on the surface) of oil-immersed transformers are calculated to be $65° + 40° = 105°C$ and $75° + 40° = 115°C$, respectively.

The temperature of oil-immersed transformers of low capacity (of the order of 25 kV A) is maintained within the

permissible limits through the dissipation of heat into the ambient air by the smooth walls of the tank. In transformers of high capacity, the cooling surface area of the tank has to be deliberately increased, or special coolers have to be used.

Overvoltages

During normal operation, the insulation of transformers is under the normal operating voltage of the network in which they are connected. But the line voltage, though momentarily, may considerably exceed the rated value. An abnormal voltage across the terminals of the transformer, which is dangerous to the transformer insulation, is referred to as *overvoltage* or a *voltage surge*. Overvoltages are classed as internal and external.

Internal overvoltages (switching surges) are those which develop as a result of changes in the operating conditions of the transformer or the system in which it operates. Such changes inevitably take place in the event of accidental short-circuits, when switching transformers and lines having large inductances and capacitances on and off, etc. The cause of these surges is a sharp change in the electromagnetic and electric fields which are in equilibrium during normal operation; in the case of a sudden change in the operating conditions, this equilibrium abruptly becomes disturbed, thus causing an increase in the voltage to a level dangerous to the insulation.

External overvoltages (lightning surges) are of atmospheric origin; they occur as a result of the action of lightning discharges. If a lightning discharge takes place in immediate proximity to the transformer or the line to which it is connected, there develops a surge as a consequence of the inductive effect of the lightning current and charge. Such a surge is said to be *induced*. A lightning surge caused by direct stroke to the line or a transmission tower is most dangerous to transformers.

Under the action of various surges, a complex electromagnetic process occurs in transformers, which in turn causes overvoltages across the winding elements inside the transformers. The magnitude of these overvoltages may

many times exceed the operating voltage. Therefore, every transformer, depending on its rated voltage and conditions of operation in an electrical system, must withstand some overvoltage.

In the Soviet Union, all transformers are grouped into the following standard voltage classes: 3, 6, 10, 20, 35, 110, 150, 220, 330, 500 and 750 kV (USSR Standard 721—74). The value, or level, of the permissible overvoltages across the winding terminals of a transformer is determined by its voltage class. The transformers of the 110-kV Class and higher use for lightning protection special devices (capacitance-grading rings and shielding turns) introduced in the structure of their windings.

Overcurrents and Dynamic Forces

Along with overvoltages, currents many times exceeding the operating ones arise in the transformer windings when any changes or disturbances occur in the transformer operating conditions, especially in the event of short-circuits. Such abnormal currents are called *overcurrents*. At the moment an unloaded transformer is swi'ched in the supply circuit the make current may exceed the ıated value 6 to 8 times. The short-circuiting of a transfoımer causes an overcurrent whose magnitude may be as great as 35 times the current rating.

The flow of so heavy a current through the transformer windings gives rise to destructive mechanical stresses which tend to burst them both radially and axially. In each winding, the current in all of the turns flows in the same direction, and so, attractive forces act between them. The forces acting between the concentrically arranged primary and secondary windings are directed radially. Since the primary and secondary currents are in opposite directions, these forces tend to repel the windings from each other; the outer winding will be expanded and will tend to rupture, whereas the inner winding will be compressed. The interaction of the radial forces F in the windings is illustrated in Fig. 1.22. In addition to the radial forces, the windings are acted upon by axial forces. Their magnitude is smaller than that of the radial forces, but they may become dangerous under

emergency operating conditions. These forces tend to burst one winding along its axis and to compress the other.

Figure 1.23 shows a diagram of forces acting in the transformer windings when one of them is higher than the other. As will be recalled, the magnetomotive forces and consequently, the mechanical stresses in the primary and secondary windings must be in equilibrium. But in the case of an axial asymmetry of the windings, this equilibrium is disturbed.

If we mentally divide the windings in half and assume that the halves of the magnetomotive forces of the corresponding windings are concentrated at the centres of these half-windings, then obviously, the forces S acting between the half-windings will be directed as shown in the figure. The radial and axial forces, F and Q, are found by resolving the forces S by the parallelogram law. As is seen from the figure, these forces tend to compress the winding having the smaller axial size and to burst the winding of the greater axial size. Therefore, to equalize the magnetomotive forces as fully as possible, the windings must be made to have one and the same height and must be arranged on the core limbs at the same level.

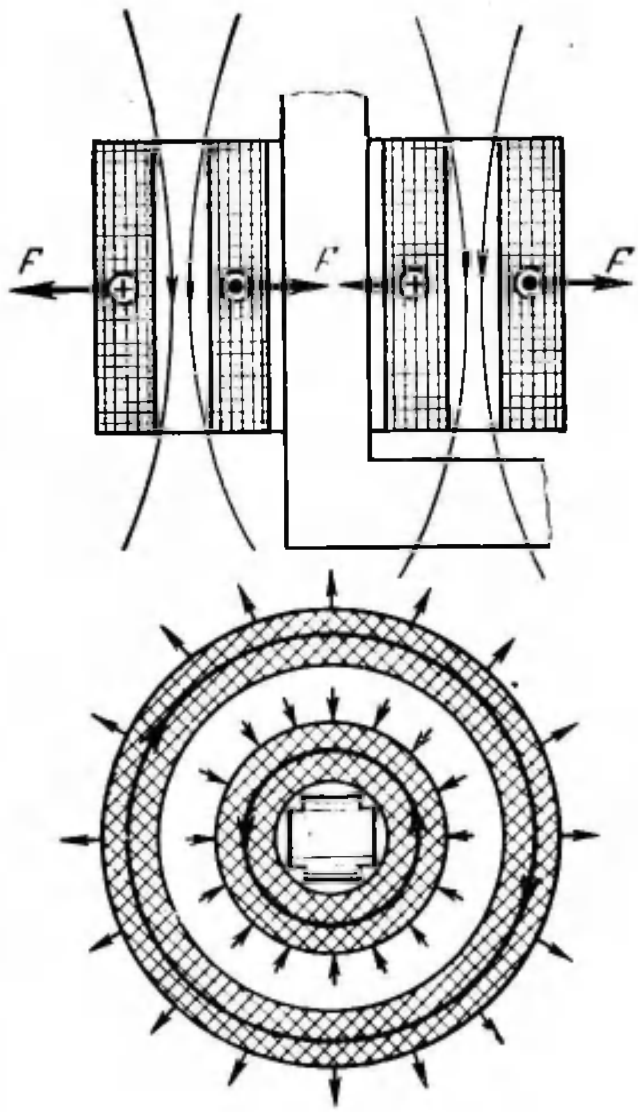


Fig. 1.22. Radial forces in concentric windings

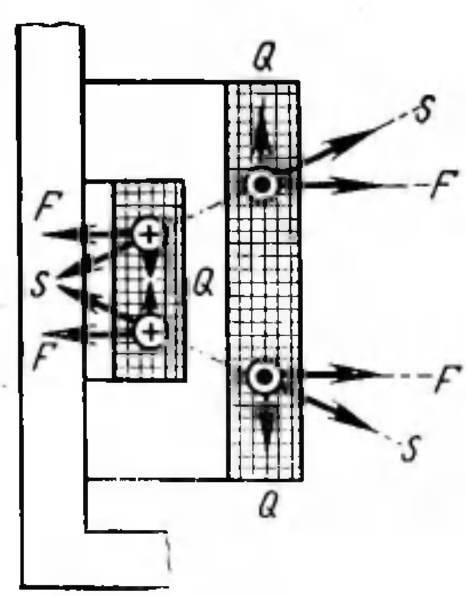


Fig. 1.23. Axial and radial forces in transformer windings

During normal operation, the passage of current through the windings also causes dynamic forces to act between the winding turns and between the windings themselves, but in this case these forces are too weak to give rise to any troubles, whereas in the event of overcurrents they grow sharply and in some instances cause heavy destructions. Moreover, overcurrents cause an excessive temperature rise of the windings and other current-carrying parts of the transformer, and this may result in damage to the transformer insulation. The windings in transformers are tightly pressed and securely clamped in place in order to prevent their mechanical destruction.

According to USSR Standard 11677—75, all power transformers must be capable of withstanding, without failures and residual deformations, dead (external) short-circuits. The permissible values of short-circuit current duration and sustained overcurrent ratio are given in the pertinent standards and technical specifications. The maximum permissible duration of a short-circuit current at the terminal bushings of a transformer should be at least a few seconds.

Thus, the transformer must meet certain requirements as to its reliability; in the first place, it must be lightning-proof, thermally stable, and dynamically strong.

1.9. Voltage Control

The operation of electric power consumers will prove economically efficient, provided the uninterrupted supply of power and high grade of electrical service are ensured. The grade of electrical service is standardized (USSR Standard 1309-67). It is characterized, first of all, by the stability of the supply voltage and frequency. The deviations of these parameters from the rated values must be kept within the limits specified by the standard. The standard 50-hertz supply frequency is maintained within the limits of tolerance by the generators of power stations, whereas the voltage level at different points of power supply networks depends on the consumer's load which is a variable.

It is a well-known fact that, depending on the season and even the time of day, the consumer's load may vary a great deal. For instance, in summer much less power is consumed

for lightning purposes than in autumn and winter. Obviously, as the load current in a power supply network changes, so does the voltage drop across the load, hence the variations in the supply voltage across consumers' terminals: it will be either too low or excessively high.

Lighting fittings are especially sensitive to the supply voltage variations: too high a voltage greatly reduces the service life of the lamps, while too low one impairs illumination. A 7- to 8-percent reduction in the supply voltage of electric furnaces makes it impossible to complete the melting of metal; such a furnace operation is considered an emergency and may entail heavy economic damages. The torque of induction motors (used mainly for electric drive purposes) is proportional to the square of the supply voltage. The standard stipulates that the supply voltage fluctuations of the motors should not exceed $\pm 5\%$ of the rated value, because a decrease in the voltage of a motor causes the braking of its rotor, an increase in the current in the rotor and stator circuits, and, as a result, the overheating of the motor, whereas an increase in the voltage brings about an undesirable reduction of the power factor and also, a rise in the motor speed and stator circuit current in excess of the rated values.

To control voltage, power transformers are equipped with special switching devices, called *tap-changers* or *tapping switches*, which are connected by leads to the voltage-control taps provided on the transformer windings. Also, application find special regulating and booster transformers capable of controlling voltage within broad limits.

Voltage control in the transformer is based on the principle of changing the transformation ratio, i.e., the number of active turns in one of the transformer windings. Let us consider this method of regulation (see Fig. 1.24). The primary (HV) winding *3* of the step-down transformer shown in the diagram is connected to a generator *1* whose output voltage is maintained at a constant value of V_1. The winding has three voltage-control taps, X_1, X_2 and X_3, connected to a tapping switch *2* whose movable contact or shoe can be placed in positions *I*, *II* or *III* corresponding to the taps. The secondary (LV) winding *4* is connected into a variable load *5*.

Assume that the rated voltage V corresponding to the middle position, *II*, of the tapping switch *2* exists across the load terminals *mn*. In this case, the HV winding turns between the taps X_1 and X_2 will carry no current.

Now, let us assume that the current on the LV side has risen, so that the voltage drop poduced by its across the

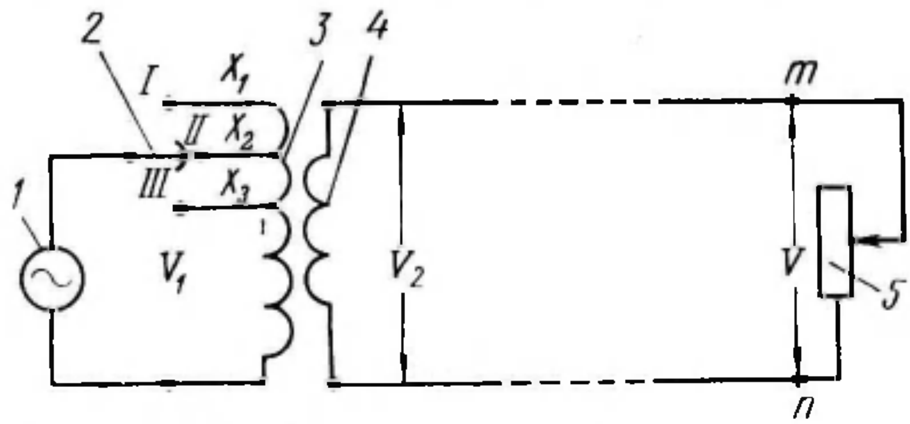


Fig. 1.24. Illustrating voltage control in a transformer

1—generator; *2*—tapping switch (tap-changer); *3*—HV winding; *4*—LV winding; *5*—load

load has increased to such an extent that the voltage across the load terminals has dropped. In order to increase this voltage, it is necessary to increase the voltage V_2 across the LV winding terminals. Since the number of turns in the LV winding remains unchanged, the only thing to do to increase the voltage is to raise the voltage induced per turn of the winding. As will be recalled, the voltage per turn is the same for any winding of the transformer and is determined by the voltage applied to, and the number of turns in, the primary winding. Therefore, with the applied voltage V_1 remaining the same, the voltage per turn and consequently, the secondary voltage V_2 and the voltage V across the load terminals can be raised by reducing the number of turns in the active part of the HV winding with the tapping switch, i.e., by shifting the shoe of the switch from position *II* to position *III*.

To lower the voltage, it is necessary to reduce the voltage per turn in the winding by putting into operation a greater number of turns on the HV side, i.e., by shifting the switch shoe to position *I*.

Various switching arrangements are used for changing the number of turns in the transformer windings. By the switching method, they are classed into on-load and off-load or

off-circuit tap-changers. The on-load tap-changer enables one to control voltage without disconnecting the transformer from the power network. The control may be effected either automatically or by hand, by using push buttons. The off-load tap-changer can only be used when the transformer is off-circuit, i.e., when all its windings are disconnected from the live network, otherwise an electric arc will strike between the tapping switch contacts at the moment the circuit is broken, which will cause damage to the transformer.

Power transformers use stepped voltage control, i.e., one whereby the number of winding turns and, correspondingly, the voltage are at once changed by a certain step when the tapping switch is shifted from one position to another.

Until recently, low- and medium-capacity three-phase transformers equipped with no-load tap-changers used a three-step voltage control, each step giving a voltage variation amounting to 5% of the rated value. In this case, the HV windings were made with three taps to obtain the following three voltage-control steps: +5% voltage step, rated voltage step, and —5% voltage step. More powerful transformers (with a capacity over 5 600 kV A) were provided with five voltage-control taps, each control step giving a voltage variation equal to 2.5% of the rated value.

According to USSR Standards 12022—66, 11920—73 and 12965—74, the method of tap changing, the number of voltage-control taps and the voltage variation provided by each control step in oil-immersed power transformers must comply with the technical specifications for the individual types of the transformers.

In transformers having a capacity of 25 kV A and more and using no-load tap-changers, provision is made for controlling voltage within ±5% of the rated value in steps of 2.5%. Depending on their capacity and voltage class, transformers using on-load tap-changers may have from 13 to 33 taps providing for voltage control in steps of 1.25 to 1.78% of the rated value.

The following three tapped-winding arrangements are basically used for controlling the voltage of transformers: arrangement with the taps placed at the neutral end of the winding, and direct and reverse arrangements with the taps placed in the middle of the windings.

The arrangement with the voltage-control taps placed at the neutral end of the winding is shown in Fig. 1.25*a*. With this arrangement, various voltage steps in a three-phase star-connected transformer are obtained by connecting together the corresponding taps of the phase windings, say taps X_1, Y_1 and Z_1, or X_2, Y_2 and Z_2, or X_3, Y_3 and Z_3, and so on (depending on the total number of the taps in each phase winding), so as to form the neutral point of the

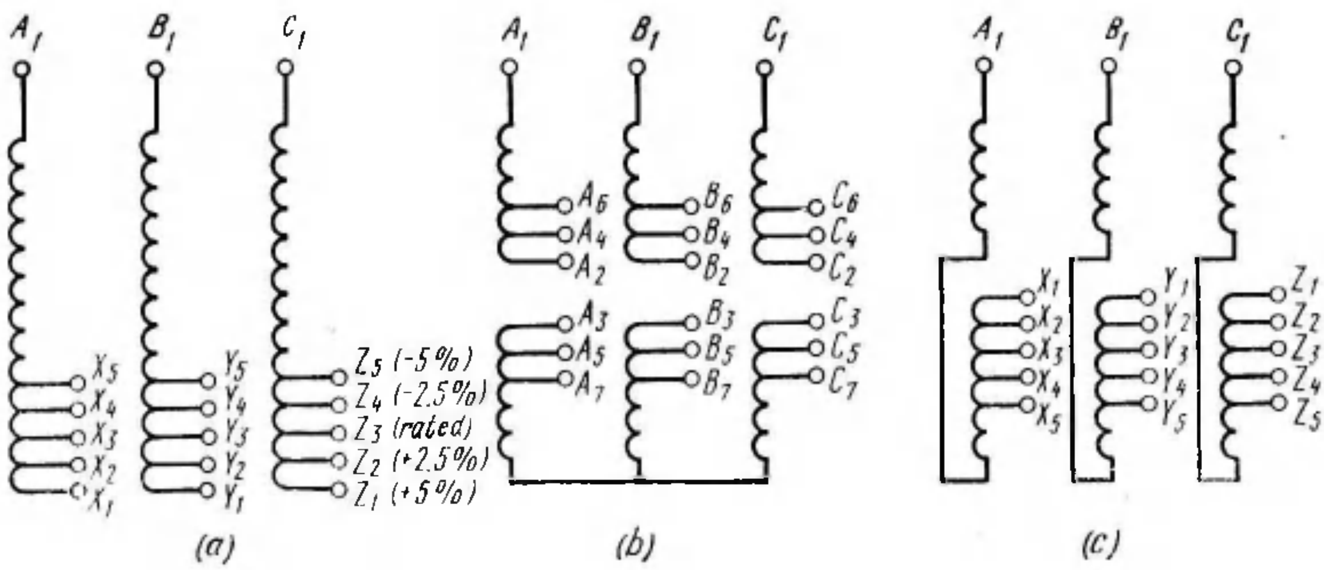


Fig. 1.25. Tapped-winding arrangements

(*a*) winding arrangement with voltage-control taps placed at the neutral end; (*b*) direct tapped-winding arrangement; (c) reverse tapped-winding arrangement

star connection. When there are five taps on each phase winding, the first connection gives the greatest number of turns (+5%), the third connection gives the rated number of turns and the fifth, the smallest number of turns (—5%). The second and fourth connections give intermediate steps: +2.5 and —2.5%, respectively. A single three-phase switch is used to change the taps. This arrangement is employed in transformers having a capacity of up to 630 kV A inclusive.

In the direct arrangement (see Fig. 1.25b), the voltage-control taps are placed in the middle of the phase windings, in "breaks". Both halves of the windings are made symmetrical. The required voltage step is obtained by appropriately connecting taps in all the three windings. Thus, by connecting phasewise the terminals A_2 and A_3, B_2 and B_3, and C_2 and C_3, the +5% voltage step is obtained. The +2.5% voltage step is obtained by connecting phasewise the terminals A_3

and A_4, B_3 and B_4, and C_3 and C_4, and the rated voltage step, by connecting the terminals A_4 and A_5, B_4 and B_5, and C_4 and C_5. The connection of the terminals A_5 and A_6, B_5 and B_6, and C_5 and C_6 gives the —2.5% voltage step and that of the terminals A_6 and A_7, B_6 and B_7, and C_6 and C_7, the —5% voltage step.

The voltage steps are designated by the Roman numerals, I, II, III, IV, and V. The numeral I corresponds to the step with the highest transformation ratio (+5%), the numeral III, to the rated voltage step, and the numeral V, to the step with the lowest transformation ratio (—5%).

Transformers having a capacity of up to 6 300 kV A and wound according to the direct arrangement for voltages of 6-35 kV use a single three-phase tapping switch, while those of a higher capacity are equipped with three single-phase switches, one for each phase.

The reverse arrangement with the voltage-control taps placed in the middle of the phase windings is shown in Fig. 1.25*c*. The operation of this winding arrangement is similar to that of the first arrangement (see Fig. 1.25*a*).

The direct and reverse tapped-winding arrangements are distinguished for the fact that the turns which are put out of operation when switching from tap to tap lie in the middle of the windings and not at their ends. As a result, the magnetic equilibrium between the primary and secondary windings is less disturbed and the axial forces acting between them are thus reduced, which makes for a greater mechanical stability of the windings (this applies more to the windings of direct arrangement). The reverse arrangement is further noted for its upper and lower portions of the windings being wound in opposite directions (one is left- and the other, right-hand). If these portions were wound in the same direction, their emf's would be opposed and the resultant emf of the winding would be zero.

The reverse winding arrangement is used in three-phase transformers with a capacity of 1 000-1 600 kV A and a voltage of up to 10 kV. When the windings are connected in a star, the reverse winding arrangement may be regarded as the one with the voltage-control taps placed at the neutral end of the winding.

1.10. Transformer Winding Arrangements for On-Load Tap Changing

Among the great variety of transformers using on-load tap changing, worthy of notice are power transformers and autotransformers equipped with built-in switching devices which make it possible to change taps and thus to maintain voltage withing the required limits directly at the transformer terminal bushings without interrupting the load.

The windings of transformers using on-load tap-changers (see Fig. 1.26) differ from those of transformers equipped with no-load tap-changers in that they have a greater number of voltage-control taps, provide for a wider voltage-control range, and are made up of two individual windings which are referred to as the excitation (or main) winding and the regulating winding (separate windings for coarse and fine voltage control may sometimes be also included). As a rule, voltage control is carried out on the HV side, therefore Fig. 1.26 shows the HV winding arrangements only. The arrangements for one phase only are shown, because all the three phase windings of the transformer are identical. The design and operation of the on-load tap-changer are considered elsewhere in the text, and here we restrict ourselves to the examination of transformer winding arrangements for use in conjunction with the on-load tap-changer.

Figure 1.26*a* shows the reverse tapped-winding arrangement. It is similar to the one examined earlier. Like all of the winding arrangements used for on-load tap changing, this arrangement includes two windings — an excitation winding *1* and a regulating winding *2*. The latter is made as a separate tapped coil and is designated *RW*. By means of a drive mechanism the movable contact (finger) of a selector switch *3* (shown schematically) of the tap-changer is moved from tap to tap without interrupting the load current, and thus the required voltage corresponding to the selected step is obtained between the points *A* and *X*.

To extend the voltage-control range, use is frequently made of an arrangement wherein the connection of the regulating winding can be reversed, i.e., changed from aiding to opposing, and vice versa, with respect to the excitation winding (see Fig. 1.26*b*). With the aiding connection of the

regulating winding (a reversing switch *4* is in position *III-I*), the number of turns being put in operation, as the

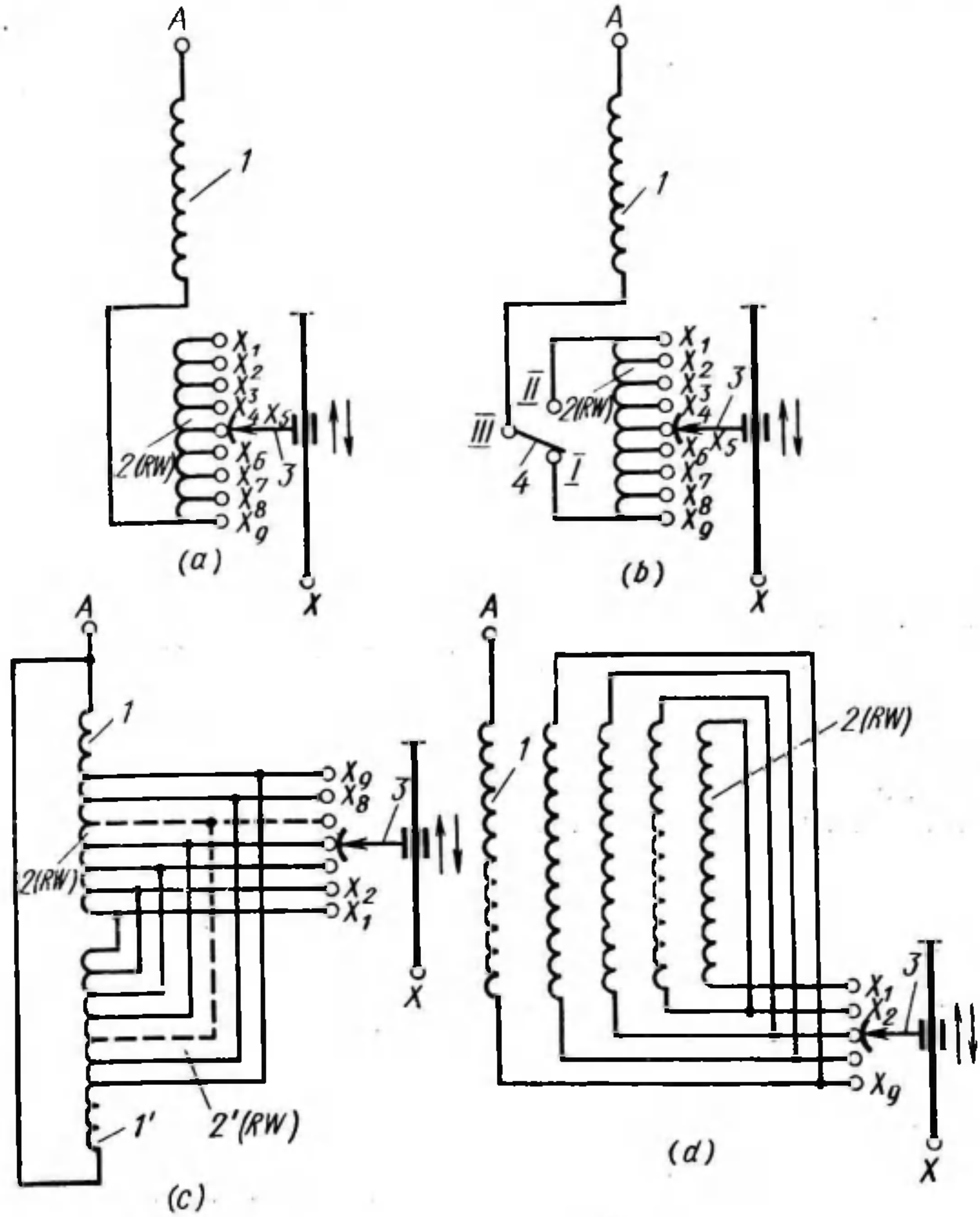


Fig. 1.26. Winding arrangements for on-load tap changing

(*a*) reverse tapped-winding arrangement; (*b*) winding arrangement with reversible regulating winding; (*c*) winding arrangement with two parallel branches; (*d*) multiply re-entrant helical-winding arrangement; *1*—excitation winding; *2*—regulating winding; *3*—selector switch; *4*—reversing switch

selector switch is shifted from position *9* to position *1*, is increased (if the windings *1* and *2* are wound in opposite directions) and in position *1* the resultant voltage of the

HV winding is raised by the total voltage range of the regulating winding. To lower the voltage, the movable contact of the selector switch is shifted back from position *1* to position *9*.

When the reversing switch is shifted to position *III-II*, the regulating winding and the excitation winding are connected in series opposition and, at the same time, the selector switch contact is shifted to position *1*. In switching from the 1st to the 9th step, the number of the opposing turns of the regulating winding grows larger and the total voltage of the HV winding is reduced. With the selector switch in position *9*, the voltage is decreased by the total voltage range of the regulating winding. Switching in the reverse direction increases the voltage.

Thus, reversing the connection of the regulating winding doubles the voltage-control range. Such an arrangement simplifies the regulating winding, but complicates the tap-changer design.

A tapped-winding arrangement with two parallel branches (see Fig. 1.26*c*) has found wide application. It ensures a better utilization of the core windows and winding wires. The upper and lower portions of the windings are strictly symmetrical; they are wound in opposite directions and consist of excitation windings *1* and *1'* and regulating windings *2* and *2'*, respectively. Because of the different directions of their turns, both winding halves can be connected in parallel and provided with common voltage-control taps.

A more perfect tapped-winding arrangement for on-load tap changing is the multiply re-entrant helical-winding arrangement having so many re-entries as there are voltage-control steps, the winding turns being uniformly spaced all along the winding (see Fig. 1.26*d*). With the winding arrangements shown in Fig. 1.26*a*, *b* and *c*, in switching from tap to tap (especially when the amount of control is large), a "dead" zone is formed in the regulating winding where the turns are put out of operation and thus do not take part in producing the magnetizing force (as measured in ampere-turns). To equalize the magnetizing forces of the primary and secondary windings, the latter have to be spread, i.e., their turns have to be pushed wider apart along the winding, in the region of the regulating winding in order to avoid heavy

leakage fluxes. The multiply re-entrant winding arrangement is free from the above shortcoming, because the disconnection of one or several voltage-control steps (winding re-entries) does not disturb the uniform distribution of magnetizing forces along the windings, and the magnetizing forces of the secondary windings thus remain equalized. Multiply re-entrant layer-by-layer windings are not very difficult to manufacture: they are wound with several parallel wires, each of which forms an individual winding re-entry serving as a voltage-control step and is provided with a voltage-control tap.

Review Questions

1. What is the no-load current? What do the no-load current and losses depend on?
2. What is the transformation ratio?
3. Tell about the short-circuit (impedance) voltage. Which are the units it is measured in?
4. What are the short-circuit losses? What do they depend on?
5. Draw the winding connection diagrams for the single- and three-phase transformers.
6. List the standard types and phase-displacement groups of winding connections for transformers and autotransformers.
7. What tapped-winding arrangements for controlling voltage do you know? What is the difference between the tapped-winding arrangements used with no- and on-load tap-changers?

CHAPTER TWO

Materials Used in Transformers

A large variety of materials is used in manufacturing and repairing transformers. Electrical materials, of which the main parts of transformers are made, are the most essential ones. Electrical materials with respect to electric current and electric and magnetic fields possess certain special properties which differ from those of other types of materials.

Electrical materials are classified as insulating (dielectrics), conductor (or conducting), and magnetic materials. Conductor and magnetic materials are frequently called active. Each material must meet certain requirements stipulated either by the State Standards or by technical specifications.

2.1. Properties of Insulating Materials

The main purpose of electrical insulating materials, as their name implies, is to insulate reliably the live parts of electrical installations from one another and from earthed structural components, therefore these materials must possess certain properties with respect to electric current. Let us consider the basic properties of electrical insulating materials.

Conductivity

In contrast to conductor materials, electrical insulating materials possess very low conductivity. The ability of dielectrics to conduct current is characterized by their volume and surface resistivities (or specific resistances). Volume resistivity is expressed in ohm-centimetres and is

designated ρ_V, while surface resistivity, designated ρ_S, is expressed in ohms. The volume resistivity of various dielectrics ranges from 10^{10} to 20^{20} ohm cm or more (its value for conducting materials ranges from 10^{-6} to 10^{-2} ohm cm). The higher the volume and surface resistivities of a dielectric, the higher its quality.

In transformer manufacture and repair, the quality of insulation is practically evaluated for the entire transformer, or for its individual parts, by applying a high voltage thereto. During this test, a current, though very small, flows through the insulation; this current is called *leakage* or *conduction current*. Its magnitude depends on the electrical resistance of the transformer insulation. Insulation resistance is designated R_{ins} and is measured in megohms or kilohms by means of an instrument called megohmmeter (1 megohm = 1 000 000 ohms; 1 kilohm = 1 000 ohms).

Insulation resistance depends on external factors, such as temperature, humidity, and surface contamination, as well as on the properties of the insulating material itself. High temperature and humidity sharply reduce insulation resistance and consequently, increase leakage current and lower the quality of the insulation.

Most insulating materials used in transformers possess high hygroscopicity, i.e., the ability to absorb moisture from air, therefore, after manufacture or repair, transformers are dried out, which greatly improves their insulation resistance.

Thus, insulating materials must have a high electrical resistance and must be moisture-resistant.

Insulation resistance is a very important factor, and it is widely used when determining the moisture content of the transformer insulation.

Dielectric Loss

A dielectric (insulation) subjected to a varying electric field produced by an alternating voltage applied to it absorbs some of the electric energy which is transformed into head in the dielectric. This loss of energy is called *dielectric loss.*

The dielectric loss (in watts) can be measured directly, or it may be calculated by the formula

$$P = V^2 \omega C \tan \delta$$

where P = power loss in the dielectric, W
V = applied voltage, V
ω = angular frequency, rad/s ($\omega = 2\pi f$, where f is the frequency of the applied voltage)
C = capacitance of the dielectric, F
$\tan \delta$ = dielectric dissipation factor (or loss tangent)

From the above formula it follows that, given the applied voltage, frequency, and capacitance of insulation, the power loss in the latter depends on the loss tangent. Therefore, the dielectric loss in insulation is customarily evaluated through the loss tangent which is one of the chief insulation characteristics.

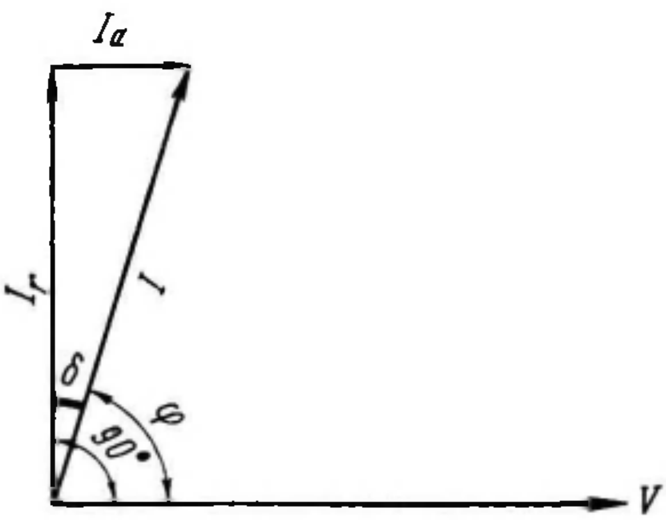


Fig. 2.1. Simplified vector diagram of currents in a dielectric

To get an idea of the loss tangent, let us consider a simplified vector diagram of current in a dielectric (Fig. 2.1). When the dielectric is subjected to an alternating voltage V, a current I flows through it. This current consists of two components — a reactive (capacitive) component I_r and an active (or real) component I_a. The angle between the vectors of currents I and I_r, which is complementary with the phase angle φ, is called the *dielectric loss angle.*

As is seen from the diagram, the tangent of the dielectric loss angle, or simply the loss tangent, is the ratio of two currents — the active component of the current in the dielectric and the reactive component:

$$\tan \delta = \frac{I_a}{I_r}$$

In practice, the loss tangent is expressed not in absolute units, but as a percentage:

$$\tan \delta \% = \frac{I_a}{I_r} \times 100$$

The loss tangent of a given material is not a constant, but a variable depending on the frequency of the applied voltage and temperature. The greater the loss tangent, all other things being equal, the higher the dielectric loss, i.e., the poorer the quality of the dielectric. At a temperature of 20°C and frequency of 50 Hz, the loss tangent of the insulating materials used in transformers ranges from 0.005 to 0.02.

The moistening of insulation causes a sharp rise of the dielectric loss in it, therefore, the loss tangent is an important characteristic for determining the moisture content of the transformer insulation. The loss tangent of a transformer grows larger not only as a result of the moistening or contamination of the insulation of the core-coil unit, but also because of a poor quality of the oil filling the transformer.

Permittivity of a Dielectric

If a voltage is applied to a dielectric, there develops an electric field under the influence of which the bound electric charges of the atoms and molecules of the dielectric will be displaced: the positive charges will be displaced in the direction of the field, and the negative charges, in the opposite direction. The atoms and molecules will then have their centres of positive and negative displaced in opposite directions and thus will form electric doublets, i.e., separated pairs of elastically bound equal and opposite charges. If the voltage is removed, the opposite will take place and the displacement of electric charges in the dielectric will disappear. The phenomenon of the elastic displacement of electric charges in the dielectric under the effect of electric field forces is called *dielectric polarization*.

Polarization varies for different materials. The greater the polarization, the higher the capacitance of the dielectric,

i.e., its ability to store electric charges. The dielectric polarization is quantitatively evaluated in terms of *relative permittivity*, designated by the Greek letter ε. If, for example, two capacitors have exactly the same geometrical dimensions, but one of them uses air ($\varepsilon \approx 1$) as the dielectric, and the other uses paper ($\varepsilon \approx 3$) for the same purpose, then the capacitance of the capacitor with paper will be approximately three times that of the capacitor with air.

Like the loss tangent, the permittivity of a dielectric depends on temperature and the frequency of the applied voltage. At a temperature of 20°C and frequency of 50 Hz, the relative permittivity of the insulating materials used in transformers ranges from 2 to 8.

The electric field strength in a dielectric is inversely proportional to its permittivity, therefore when selecting insulating materials which are to operate in series, one tries to have their permittivities as close as possible. This ensures a uniform distribution of the electric field in the composite insulation and thus improves its electric strength. With an unhappy choice of the permittivities and thicknesses of the insulation components, the electric field strength may exceed the electric strength of the insulation and it will fail.

Electric Strength

If a voltage is applied to an insulating material and is increased gradually, an instant will then come when the quality of the insulation will sharply deteriorate and its electrical failure or breakdown will ensue. As a result of breakdown, the insulation resistance drops sharply, which causes a short-circuit between current-carrying parts.

Insulation breakdown in high-capacity transformers entails heavy destructions accompanied with arcing and fusion of metal structural components. The voltage at which breakdown of insulation occurs is called *breakdown* voltage. It is designated V_{br} and is expressed in kilovolts.

The property of an insulating material which enables it to withstand high voltages without injury, is expressed in terms of the minimum electric field strength (or electric

stress) which will cause breakdown of the dielectric, i.e., in terms of the breakdown voltage per unit thickness of the dielectric:

$$E_{br} = \frac{V_{br}}{h}$$

where E_{br} = breakdown stress, kV/mm
V_{br} = breakdown voltage, kV
h = thickness of the dielectric, mm

The breakdown stress of a dielectric is referred to as the *electric strength* (or dielectric strength) of the material. It is one of the main insulation characteristics. The average electric strength of the insulating materials used in transformers ranges from 5 to 90 kV/mm at 20°C.

Other Properties of Electrical Insulating Materials

For a long and reliable operation, insulating materials must possess a number of special properties other than electrical, chief among them being thermal stability, mechanical strength, elasticity, flexibility, oil resistance, moisture resistance, and chemical resistance. This means that insulation must withstand elevated temperatures, mechanical forces, and the effects of moisture, chemicals and other substances for prolonged periods without serious deterioration of its essential properties (mainly electrical and mechanical).

According to their thermal stability, electrical insulating materials are grouped into the following seven classes: V, A, E, B, F, H, and C (USSR Standard 8865-70). The standard establishes the maximum temperatures which the materials of each class can withstand for prolonged periods.

Most insulating materials used in transformers belong to Class A; the limiting temperature for this class is 105°C. The class embraces fibrous cellulose or silk materials impregnated with, or immersed in, a dielectric liquid, and also other materials or their combinations capable of operation at the Class A temperature.

2.2. Insulating Materials Used in Transformer Repair Work

Electrical Insulating Papers and Pressboards

Electrical insulating papers are made from kraft pulp of light brown (natural tan) colour on special paper machines and are available in rolls. These papers are classified according to their types and purpose.

Cable Paper. The following grades of cable paper are mostly used in transformers: K-080 (0.08 mm thick), K-120 (0.12 mm thick) and K-170 (0.17 mm thick). The electric strength of dry cable paper ranges from 6 to 9 kV/mm, but when the paper is impregnated with dry transformer oil, its electric strength comes to 70-90 kV/mm, depending on the thickness of course. The relative permittivity of dry cable paper is 2.2-2.7 and density 0.8 g/cm^3. It is available in rolls 500, 650, and 750 mm wide.

The high electric strength and sufficient mechanical strength of cable paper make it suitable for insulating coil layers, winding wire and taps, leads, and other elements. Its resistance to hot transformer oil is fairly high.

Telephone-Cable Paper (USSR Standard 3553—73) is available in Grades KT-04 (0.04 mm thick) and KT-05 (0.05 mm thick) and is made in rolls 500 mm wide. Telephone-cable paper, like cable paper, is used as turn-to-turn and interlayer insulation in transformers.

Crepe Paper. Grade ЭКТ (USSR Standard 12769—67) provides up to 70% elongation, thanks to its transverse wrinkles (corrugations). It is available in strips 12, 15, 20, 25, 30, and 40 mm wide, wound on bobbins 200-250 mm in diameter, and also in rolls 500-900 mm wide. Its thickness is 0.5 mm (0.17 mm when smoothed out). Crepe paper is somewhat inferior to cable paper in electrical properties. It is used for insulating winding taps, for it has high electric strength, oil resistance, and elasticity, and good ability to stretch to the required shape.

Pressboard is made from unbleached sulphate pulp. Pressboard in combination with transformer oil is the main insulating material in high-voltage transformers. According

to its thermal stability, pressboard belongs to Class A insulation. Its electric strength depends on thickness and ranges from 7 to 15 kV/mm in air and from 30 to 55 kV/mm in hot (90°C) transformer oil (after preliminary drying in a vacuum followed by impregnation with dry transformer oil at 100 ± 5°C). The relative permittivity of pressboard is 4.3-4.5 and density, about 1 g/cm^3.

Pressboard is intended for immersion in transformer oil at up to 105°C, and has high mechanical strength, low shrinkage, and good ability to resist creeping discharges.

According to USSR Standard 4194—68, electrical insulating pressboard is put out in the following four grades: А, Б, В, and Г.

Grade A is intended for making major insulation components for oil-immersed transformers operating at voltages up to 750 kV inclusive. It is available in thicknesses of 2, 2.5, and 3 mm, and is made in sheets measuring 3 000 mm by 4 000 mm, 3 000 mm by 2 000 mm, 1 500 mm by 1 000 mm, and 1 000 mm by 1 000 mm (the second dimension is along grain).

Grade Б has medium hardness and improved electrical properties, and is used for making major insulation components for oil-immersed transformers operating at voltages up to 220 kV inclusive. It is available in thicknesses of 1, 1.5, 2, 2.5, 3, 4, 5 and 6 mm, in the same sheet sizes as Grade **A.**

Grade В has increased hardness and low compressibility. It is intended for making longitudinal insulation components for oil-immersed transformers, and is available in the same thicknesses and sheet sizes as Grade A.

Grade Г has medium density and increased resistance to cleavage. It is the chief material for making adhesive-bonded insulation components for oil-immersed transformers, and is available in thicknesses of 0.5, 1, 1.5, 2, 2.5, and 3 mm. Pressboard 1 mm thick is made in sheets measuring 850 mm by 1 100 mm, 850 mm by 1 000 mm, and 850 mm by 850 mm, and that over 1 mm in thickness, in sheets measuring 1 850 mm by 3 850 mm, 1 650 mm by 3 800 mm, 850 mm by 1 100 mm, 850 × 1 000 and 850 mm by 850 mm. Pressboard 0.5 mm thick is put out in rolls not less than 980 mm wide.

Varnished Cloth and Textile Materials

Varnished Cloth is a cotton or silk fabric impregnated with an insulating varnish. It is characterized by high electric and mechanical strength and good elasticity. According to its thermal stability, varnished cloth belongs to Class A insulation. Varnished cloth may be either clear (yellow) or black, depending on the kind of impregnating varnish.

Grade ЛХММ-105 (USSR Standard 2214—70) is a clear varnished cloth intended for use in oil-immersed transformers. It is available in thicknesses of 0.1, 0.2 and 0.25 mm. The electric strength is about 60 kV/mm.

Grade ЛХМС-105 is used in dry-type transformers (its use in transformer oil is also permissible).

Grade ЛХМ-105 is intended for use in dry-type transformers only.

Varnished Glass Cloth is a glass fabric impregnated with a special insulating varnish. It is available in Grades ЛСМ, ЛСК, and ЛСБ, has increased thermal stability, and is mainly used in dry-type transformers for insulating winding taps and soldered connections.

Varnished cloth is cut on the bias into strips or tapes, because the bias cut has more stretch, thus producing a tight, smooth wrap free of voids.

Cotton Tape. In oil-immersed transformers application find linen-finished tape (taffeta pattern) 0.25 mm thick and from 10 to 50 mm wide, and surgical tape (herringbone pattern) 0.45 mm thick and from 10 to 60 mm wide. Tapes are available in rolls, each roll holding 50 m of tape. Similar tapes woven from glass fibres are used in dry-type transformers. Cotton tapes are used for mechanical protection of the main insulation.

Laminated Phenolic Products

Paper-Base Laminated Phenolic Plate (USSR Standard 2718—74) for electrical application is made from special paper impregnated with a phenolic resin varnish. Transformers use Grades V-1 and V-2 laminated phenolic plate

up to 50 mm thick, which is characterized by high mechanical and electric strength. The electric strength of this material ranges from 16 to 80 kV/mm, if measured across laminations; when measured along laminations, it is several times lower.

Fabric-Base Laminated Phenolic Plate for electrical application is made from cotton cloth impregnated with a phenolic resin varnish. The fabric-base laminated plate is somewhat inferior to the paper-base laminated plate in electrical properties, but it has a higher impact strength and is therefore used for making insulation components subjected to mechanical load.

Glass-Fabric-Base Laminated Phenolic Plate is made from glass cloth impregnated with a phenolic resin varnish. It possesses high thermal stability, moisture resistance, and mechanical strength, and is mainly used in dry-type transformers.

Paper-Base Laminated Phenolic Tubes and Cylinders (USSR Standard 8726—72) are formed by rolling sheets of paper coated on one side with a phenolic resin varnish on metal mandrels between heated pressure rolls. As a result, the paper laminations become cemented together. The setting is completed in a baking oven to give hard, high-strength tubes and cylinders.

Paper-base laminated phenolic tubes and cylinders are oil-resistant and have a fairly high electric strength. They are intended for operation in air and in transformer oil at temperatures from —40 to +105°C.

The tubes are used for insulating leads and core studs, and also for making operating rods (shafts) of tapping switches. The cylinders are mainly used for insulating transformer windings from one another and from core limbs, and also to insulate tapping switches.

The tubes are available in inside diameters from 10 to 80 mm, and cylinders, in inside diameters from 85 to 1 200 mm and lengths from 200 to 2 000 mm.

The following grades of paper-base laminated phenolic tubes and cylinders are manufactured: ТБ (tubes), ТБ/П (tubes with guaranteed electric strength along laminations, for tapping switches), and ЦБ (cylinders).

Transformer Oil

Transformer oil is a product of fractional distillation of petroleum. In oil-immersed apparatus and transformers, it doubles as an insulation and a cooling (heat-transfer) agent. Transformer oil must be free from moisture, mechanical impurities, tar-forming substances, and other materials having poor dielectric properties. Moisture and impurities sharply lower the electric strength of transformer oil. The oil from which free moisture has been removed is called dry oil.

It is undesirable to mix oils having different characteristics (density, congealing point, viscosity, origin, degree of purification, etc.) since this lowers the quality of the oil and accelerates its ageing. To improve the stability of the oil, various additives are used, such as Grades ВТИ-1, ДБК, and the like.

Chief Characteristics of Transformer Oil

Density at 20°C, g/cm^3	0.84 to 0.89
Acid Number, mg KOH per gram, not more than	0.02 to 0.05
Congealing Point, °C, not higher than	—45
Flash Point, °C, not lower than (depending on the oil grade)	135 to 150
Kinematic Viscosity at 20°C, cSt, not higher than (depending on the oil grade)	30
Kinematic Viscosity at 50°C, cSt, not higher than (depending on the oil grade)	9.6
tan δ at 20°C, %, not more than (depending on the oil grade)	0.2 to 0.3
tan δ at 70°C, %, not more than (depending on the oil grade)	1.5 to 2.5
ε at 20°C	2.1 to 2.4
E_{br} at 20°C and 50 Hz, kV/mm	15 to 20
Volume Resistivity at 20°C, ohm cm	10^{14} to 10^{15}

The loss tangent values for operating transformers are given in Table 8.4 (see page 324).

Insulating Varnishes, Enamels, and Resins

ГФ-95 Varnish (USSR Standard 8018—70) is an insulating and impregnating varnish of light yellow colour. It is used for impregnating transformer windings in order to increase

their mechanical strength. The varnish is baked at 105 to 110°C for 15 hours. It is recommended not to bake it at a temperature lower than 100°C, since in this case the varnish film obtained has lower moisture resistance and also softens when heated. Moreover, the duration of baking is nearly doubled.

МЛ-92 Varnish (USSR Standard 15865—70) is an electrical insulating varnish obtained by adding 15% of the K-421.02 melamine-formaldehyde resin to the ГФ-95 varnish. It is used for the same purposes as the ГФ-95 varnish. The duration of baking for the windings impregnated with the МЛ-92 varnish is reduced to 10-12 hours, and the baking temperature, to 95-100°C. In addition, the melamine-formaldehyde resin present in the varnish makes it more oil-resistant.

Phenolic (Bakelite) Varnish is a solution of a phenolic resin (bakelite) in ethyl alcohol. The colour of the varnish is from reddish to reddish-brown. It is baked at 120 to 130°C.

Grade ЛБС-1 (USSR Standard 901—71) is used for cementing transformer insulation components, such as pressboard strips, rings, and so on. The bonded components thus obtained have high mechanical and electric strength. The solvent for the varnish is spirit.

Varnish No. 302 is an electrical insulating varnish made of rosin, tung oil, kerosene, and other components.

It is used for varnishing electrical sheet steel. The varnish film obtained after baking has high mechanical strength and moisture resistance. The duration of baking depends on temperature: at 100°C the varnish is baked for 5 to 6 hours, at 215°C it is baked for a few minutes, and at 450 to 550°C, a minute is quite enough to bake the varnish. The colour of the baked film on the sheets is from light to dark brown. The solvent for the varnish is pure, filtered kerosene.

Varnish No. 202 is used for the same purposes as No. 302. The difference between these two varnishes is that No. 202 is made with linseed oil as the base, whereas No. 302 uses tung oil (oil from tung tree nuts).

КФ-965 Varnish (USSR Standard 15030—69) is used in place of the costly varnishes Nos. 302 and 202.

Varnish No. 458 is a black oleobituminous baking varnish. It is used for impregnating the windings of low-voltage dry-

type transformers. The solvents for the varnish are petrol, toluene, and benzene. The varnish is baked at 105°C for not more than 4 hours.

ГФ-92-ГС Enamel (USSR Standard 9151—59) is a grey oleoglyptal (alkyd) baking enamel. The solvent for the enamel is a mixture of white spirit and toluene in equal proportion. The enamel is oil-resistant, and is baked at 105 to 110°C for 3 hours. The baked enamel film is strong mechanically, has a glossy surface, and protects the main insulation against arcing and creeping discharges of short duration. The enamel is used for coating the windings impregnated with the ГФ-95 and МЛ-92 varnishes, and also for painting steel structural components in dry-type transformers. Lately, the ХВ-124 grey enamel has been used for the same purposes.

ГФ-92-ХС Enamel (USSR Standard 9151—59) is a grey oil-resistant air-drying enamel. It is used as a coating enamel in dry-type transformers. It dries at 18 to 22°C in 24 hours. The solvent for the enamel is a mixture of white spirit and toluene in equal proportion.

ГФ-92-ХК Enamel is a red oil-resistant air-drying enamel which is used for coating bare leads and steel structural components.

624С Enamel (USSR Standard 7462—73) is a grey air-drying nitro enamel. It is used for painting the inside surfaces of transformer tanks. The thinner for the enamel is solvent No. 646. The enamel forms a smooth, even, and hard film. The duration of drying is 10 to 12 minutes at 20°C.

Enamels Nos. 1202 and 1201 are air-drying nitro enamels. Thanks to their good oil resistance and thermal stability, these enamels are suitable for coating current-carrying busbars and steel structural components. They dry within 10 to 15 minutes at 20°C. Thinned with solvent No. 646.

ПФ-133 Enamel (USSR Standard 926—63) may be black or grey. It is used for painting the outside surfaces of tanks, coolers, and thermosiphon filters, and other transformer surfaces which have no contact with oil. The time of drying in air at 20°C is 30 to 36 hours; at 80°C the enamel dries in 1.5 hours. The enamel is thinned with a solvent, such as xylene, turpentine oil, or a mixture of these substances with

petrol or white spirit, the content of the latter in the mixture being not higher than 50%.

ФЛ-03-К Primer (USSR Standard 9109—59) is used on transformer parts and units (tanks, conservators, covers, coolers, etc.) preparatory to painting with Grade ПФ-133 enamel. The drying time at 100 to 110°C is within 30 minutes.

Colophony or Rosin is a product obtained as a result of distilling the crude turpentine of various coniferous trees, mainly pine. The melting point of rosin is about 100°C. It is used as a flux when soldering and tinning with tin-base solders.

2.3. Conductor and Magnetic Materials

Conductor Materials

Among conducting materials, copper and aluminium have found the widest application in electrical devices.

Red Electrolytic Copper is used for making conductors. It is characterized by high purity and excellent quality. Copper has the lowest resistivity of all the conducting materials except silver: 0.0175 ohm mm²/m (at 20°C). Grade ПММ soft (annealed) copper wire is used for making windings. Grade ПМТ hard copper wire is used for making current-carrying bars, busbars, rods, overhead wires, and other current-carrying parts which must have high mechanical strength.

Aluminium is inferior to copper in conductivity and mechanical strength. Its resistivity is 0.029 ohm mm²/m (at 20°C), which is 1.65 times higher than the resistivity of copper. Therefore, if it is necessary to replace a copper conductor by an aluminium one, the cross section of the latter should be taken 1.65 times greater than that of the former. However, the low cost, light weight, and comparatively low resistivity of aluminium make for its wide use in electrical engineering. The grade designation for soft aluminium wire is ПАМ, and that for hard aluminium wire, ПАТ.

Copper and aluminium winding wire may be round or recangular in section. Under USSR Standards 16512-70 and

Table 2.1

Nominal Size Ranges for Various Grades of Winding Wire (USSR Standards 16512—70 and 16513—70)

Wire Section	Nominal Wire Size for Grades					
	АПБ	ПБ	АПБУ	ПБУ	АПБД	ПБД
Round: Diameter, mm	1.35-8.0	1.2-5.2	—	—	1.35-8.0	0.38-5.2
Rectangular: Side a, mm	1.81-7.0	1.0-5.6	1.81-5.5	1.8-5.6	1.81-7.0	0.90-5.6
Side b, mm	4.10-18.0	3.0-19.5	6.90-22.0	6.7-19.5	4.10-18.0	2.10-15.0

Table 2.2

Nominal Two-Side Insulation Thickness

Wire Grade and Section	Nominal Two-Side Insulation Thickness, mm								
ПБ and АПБ:									
Round	0.30	0.72	0.96	1.20	1.68	1.92	2.88	4.08	5.76
Rectangular	0.45	0.55	0.72	0.96	1.20	1.35	1.68	1.92	—
ПБУ and АПБУ: Rectangular	2.00	2.48	2.96	3.60	4.08	4.40	—	—	—
ПБД:									
Round	0.22	0.27	0.33	—	—	—	—	—	—
Rectangular	0.27	0.33	0.44	—	—	—	—	—	—
АПБД:									
Round	0.27	0.33	0.35	—	—	—	—	—	—
Rectangular	0.27	0.33	0.44	0.47	—	—	—	—	—

16513—70, winding wire is available in several grades, including the following;

ПБ—copper wire insulated with tapes of cable or telephone-cable paper;

ПБУ—copper wire insulated with tapes of high-voltage cable paper of increased density;

АПБ—aluminium wire insulated with tapes of cable or telephone-cable paper;

АПБУ—aluminium wire insulated with tapes of high-voltage cable paper of increased density;

ПБД—copper wire insulated with two layers of cotton yarn;

АПБД—aluminium wire insulated with two layers of cotton yarn.

According to its thermal stability in impregnated state, the insulation of the above wire grades belongs to Class A (105°C). The minimum permissible ambient temperature for these wire grades is —60°C.

USSR Standards 16512—70, 16513—70, and 434—71 specify the sizes of round and rectangular wire put out by the industry, which include the nominal diameters (d and D) for round wire, sizes on the small side (a and A) and on the large side (b and B) for rectangular wire. and cross-sectional areas.

Table 2.1 gives the nominal size ranges for various grades of winding wire, and Table 2.2, the nominal two-side insulation thickness.

Grade ПБОТ round flexible cable (USSR Standard 10787—68) is used for making leads in high-capacity power transformers. It is a single-core cable consisting of a large number of separate fine wires and insulated with several layers of cable paper covered on the outside with a cotton sheath. According to the thickness of the paper insulation, this cable is available in the following grades: ПБОТ-3, ПБОТ-6, and ПБОТ-8. The standard cross-sectional areas (in mm^2) are as follows: 16, 25, 50, 70, 95, 120, 150, 240, 300, 400 and more.

Magnetic Materials

Transformer cores are made of electrical-sheet or strip steel. It is distinguished among other types of steel for its high magnetic permeability and low loss per kilogram. Transformers of Soviet make have their cores made from hot-rolled electrical-sheet steel Grades Э42 and Э43, and cold-rolled electrical sheet steel Grades Э330 and Э330A.

The cold-rolled steel differs from the hot-rolled one in that it has materially lower loss per kilogram, increased magnetic permeability, and higher induction, so with this steel, the no-load losses, mass, and overall size of transformers can be reduced. The cold-rolled steel is also noted for the fact that when it is magnetized in the direction of rolling, the steel exhibits much higher magnetic permeability and lower loss per kilogram than when it is magnetized in the transverse direction. Therefore, transformer core laminations are punched from this steel in such a manner, as to ensure that the direction of the lines of magnetic force in them coincides with the rolling direction.

In the hot-rolled steel this anisotropy is much less pronounced, and when punching laminations, one has only to see to it that the long sides of the core limb and yoke laminations are with the rolling direction.

The maximum induction for the cold-rolled steel is about 1.7 T, and for the hot-rolled one, 1.45 T. Nowadays, the transform-building industry uses the cold-rolled electrical-sheet steel only.

2.4. Auxiliary Materials Used When Repairing Transformers

Metal alloys which serve for soldering and tunning metal articles are called *solders*. The joining of heated metal parts by means of molten solders is referred to as *soldering*. *Tinning* is a process of coating metal surfaces with a thin layer of molten solders. Various fluxes are used when soldering and tinning with solders. *Fluxes* are substances which in the molten state possess the property of dissolving oxides usually present on the metal surfaces subjected to soldering. Flux-

es provide for good wetting with molten solder of the metals being soldered and ensure a firm joint between them.

When repairing transformers, use is made of tin solder Grades ПОС-40 and ПОС-30 (USSR Standard 1499—70) for soldering and tinning copper conductors, busbars, leads, and other current-carrying components.

ПОС-40 Solder is a tin-lead alloy of the following composition: 40% tin, 58-58.5% lead, and 2-1.5% antimony. It is used for soldering winding wire of small cross-sectional area and leads.

ПОС-30 Solder consists of 30% tin, 68-68.5% lead, and 2-1.5% antimony. It is used for tinning taps, leads, and copper strips.

The melting point of solder drops with an increase in its tin content. Thus, Grade ПОС-40 solder has a melting point of 235°C, while that of Grade ПОС-30 is 245°C. Tin-lead solders are customarily called soft solders; they are being increasingly substituted by hard (or spelter) solders Grades МФ-3, ПСр-15, and others.

Grade МФ-3 Solder (USSR Standard 4515—48) is a phosphorous copper alloy consisting of 96-97% copper and 4-3% phosphorus. Its melting point is 715 to 730°C. Brazing with this solder ensures high mechanical strength of the joint, though the process is comparatively simple. The solder is widely used for brazing coil leads in transformer manufacture and repair.

Grade ПСр-15 Solder (USSR Standard 8190—56) is a silver alloy of the following composition: 80% copper, 15% silver, and 5% phosphorus. The solder gives high-quality, high-strength brazed joints, and brazing with it presents no difficulties. The melting point of the solder is 810°C, and it is used for brazing winding wire when making windings.

Oil-Resistant Rubber is used for sealing flanged joints, terminal bushings, tapping switch drives, and other detachable joints in oil-immersed transformers. The widest application have found plate and roll rubber 6 to 12 mm thick, and also strip rubber 6 mm by 15 mm, 8 mm by 20 mm, 12 mm by 30 mm, and 16 mm by 35 mm in section.

Soviet transformer makers use Grade MT oil-and-heat-resistant rubber and Grade MTM oil-and-heat-and-frost-resis-

tant rubber. The former is intended for operation within the temperature range from —45° to +100°C, and the latter, from —55° to +100°C. Rubber is available in plates 250 to 1000 mm long and 250 to 800 mm wide, and in rolls 200 to 800 mm wide, each roll holding from 500 to 2500 mm of rubber. Plate and roll rubber Grades MT and MTM are manufactured according to USSR Standard 12855—67, and strip rubber, according to technical specifications.

Grade ЛСБ-Т Glass Binding Tape (Technical Specifications ОБТ 503.001-70) is used for binding transformer core limbs. The tape is 0.2 mm thick and 20 mm wide.

Beech. Beechwood possesses good electrical and mechanical properties and is therefore used in transformers as an insulating and structural material. Prior to use, beechwood is dried and impregnated with transformer oil. It is employed for securing winding taps and tapping switches, and also as a supporting insulation for windings.

Yellow-Lead-Glycerine Cement is used for cementing porcelain terminal bushings to metal flanges. The cement is featured by fast setting and is strong mechanically. It is prepared immediately before using by mixing powdered yellow lead (lead oxide) with chemically pure glycerine diluted with distilled water to a density of 1.23 g/cm^3. If the density of the glycerine used is lower than 1.23 g/cm^3, the setting of the cement will be retarded and the resulting cement stone will be porous. The cement is prepared in the following proportion: two parts (by mass) of yellow lead per part of glycerine. When preparing the cement, it should be borne in mind that the lead oxide is highly toxic and affects the respiratory tract and skin. Because of the high cost of yellow lead, the cement is only used when it is necessary to fit rapidly a small number of terminal bushings at a time.

Magnesite Cement is used for the same purposes as the yellow-lead-glycerine cement. A batch of the cement consists of 130 g magnesite, 70 g porcelain powder, and 165 g magnesium chloride. The crystalline magnesium chloride is dissolved in hot water in a proportion of two parts (by mass) of magnesium chloride per part of water.

At present, cements have but limited application. They are only used when repairing cemented terminal bushings

fitted on comparatively old transformers. Modern transformers are equipped with built-up (detachable) bushings.

Asbestos is a fibrous mineral material. Asbestos tapes, cloths, sheets, cords, and other articles are featured by high heat resistance. It is a good heat-insulating material. Asbestos cord is used for sealing steel plugs, studs, and fittings. When impregnated with a suitable fat, it is used as a stuffing in sealing glands. Asbestos sheets and cloth are employed to heat-insulate the tanks of transformers subjected to drying.

Silica Gel (USSR Standard 3956—54) is a silicate material in the form of glassy grains or lumps. It possesses high porosity and the ability to retain moisture and the tiniest particles of tar-forming substances when transformer oil flows through it. Therefore, silica gel is used as an adsorbent for regenerating transformer oil. Depending on the pore size and grain shape, silica gel is classified as fine-pore, coarse-pore, lump, and granulated. Granulated silica gel is distinguished from lump one by the oval or spherical shape of its grains. Lump silica gel Grades KCM and KCK, and granulated silica gel Grade KCM are used for filling thermosiphon filters and breathers of transformers.

Zeolites form a group of minerals comprising complex compounds of silica and alumina. Natural zeolite occurrences are comparatively rare, and what is more, natural zeolites are frequently contaminated with other minerals which disturb their uniform structure, therefore zeolites for adsorption purposes are synthesized. By their properties and composition, synthetic zeolites are close to natural ones and comprise hard cylindrical granules (grains) having a pink tint.

Zeolites possess extraordinarily good adsorptive properties, and are widely used for deep dehydration of transformer oil. The adsorptive properties and selectivity of zeolites are explained by the fairly high porosity of their crystals whose inlet pore openings and channels of a certain definite size act like sieves that sift the molecules entering into the composition of the substance being purified.

Another important factor in the adsorption mechanism of zeolites is the fact that their surface exhibits an electrostatic property and attracts water molecules which are polar. If moist oil is passed through zeolites, all the moisture present in the oil will be adsorbed in a single cycle, while the

other oil components, including additives which improve the quality of the oil, will remain unchanged. Transformer oil is desiccated with sodium zeolites of the NaAl type, whose granules measure 4 to 6 mm.

Review Questions

1. Tell about the chief properties of electrical insulating materials.
2. Which grades of paper, pressboard, and varnished cloth are used in transformers?
3. Tell about the purposes, properties, and characteristics of transformer oil.
4. Which grades of varnishes are used for insulating electrical steel sheets and for impregnating transformer windings?
5. What is the difference between the cold-rolled and hot-rolled electrical steel?
6. Which grades of solders are used when making transformer windings and when connecting taps?
7. Tell about the basic properties of silica gel and zeolites. What are their purposes?

CHAPTER THREE

Transformer Design

The mechanical structure of a transformer depends on its purpose and field of application. However, in our discussion of the general design of transformers, we shall refer to the general-purpose three-phase oil-immersed power transformer, for this type of transformer is most common.

3.1. Classification and Designations

Power, special-purpose, and other transformers are built for definite standard capacities. Until 1962, the three-phase oil-immersed power transformers of voltage classes up to 35 kV inclusive were built to have the following kV A ratings: 10, 20, 50, 100, 180, 320, 560, 750, 1 000, 1 800, 3 200, 5 600, and higher. The three-phase transformers of Voltage Class 110 kV and higher were manufactured for kVA ratings of 5 600, 7 500, 10 000, 15 000, 20 000, 31 500, 40 000, 60 000, and higher. In 1962, a new standard (USSR Standard 9680-61) was put in force, which established the standard transformer capacity scale. According to this scale, the kV A ratings of three-phase transformers and autotransformers must conform to the following series:

10		16		25		40		63	
100		160		250		400		630	
1 000		1 600		2 500		4 000		6 300	
10 000		16 000		25 000	32 000	40 000		63 000	80 000
100 000	125 000	160 000	200 000	250 000	320 000	400 000	500 000	630 000	800 000
1 000 000	—	—	—	—	—	—	—	—	—

The rated capacities of single-phase transformers and autotransformers are one-third of the ratings in the above series

According to the voltage class of their HV windings and rated capacity (as per the standard scale), power transformers are classified conventionally into seven sizes (see Table 3.1).

Table 3.1

Classification of General-Purpose Power Transformers by Sizes

Size	kV A Rating	Voltage Class, kV
I	16 to 100	6 and 10
II	125 to 630	6, 10 and 35
III	1 000 to 6 300	6, 10 and 35
IV	10 000 to 80 000	35
	2 500 to 80 000	110
	Up to 40 000	150 and 220
V	100 000 to 400 000	110
	63 000 to 320 000	150 and 220
	400 000 and higher	150 and 220
VI	All transformers and autotransformers of voltage Classes 330 and 500 kV	
VII	All transformers and autotransformers of Voltage Class 750 kV and higher	

Note. Transformers whose rated capacity or voltage class do not conform to the standard scale are referred to the size group including transformers with the nearest capacity or voltage class.

Each type of transformer is given a designation (marking) composed of letters and numerals. The letters in the type designations of transformers manufactured in the Soviet Union have the following meaning:

О — single-phase unit;
Т—three-phase unit;
Н—on-load tap changing;
Р—split-winding unit;
Г—lightning-protected unit (with a special capacitive protection);
С—dry-type unit (self-air cooling);
М—oil-natural cooling;

Д—oil-natural air-blast cooling;
ДЦ—forced-oil air-blast cooling;
МВ—coil-natural and water cooling;
Ц—forced-oil and water cooling.

The repeated use of the letter T in the type designation of a three-phase transformer, or its use in the type designation of a single-phase unit, means that the transformer is triple-wound.

The letter designation is followed by a fractional number with the numerator giving the kV A rating of the transformer and the denominator indicating the voltage class (kV) of its HV winding.

For example, the standard type designations given below read as follows:

ТМ-100/6—three-phase, oil-natural-cooled transformer with a capacity of 100 kV A and a voltage of 6 kV on the HV side;

ТДГ-10 000/110—three-phase, oil-natural air-blast-cooled, lightning-protected transformer with a capacity of 10 000 kV A and a voltage of 110 kV on the HV side;

ТДТГ-20 000/110—three-phase, oil-natural air-blast-cooled, triple-wound, lightning-protected transformer with a capacity of 20 000 kV A and a voltage of 110 kV on the HV side;

ТС-630/10—three-phase, dry-type transformer with a capacity of 630 kV A and a voltage of 10 kV on the HV side.

The letter designations of autotransformers contain a letter A either at the beginning or at the end. The letter A at the beginning of a letter designation means that the given autotransformer is of the step-down type, whereas the one added at the end of a designation means that the autotransformer is of the step-up type. For example, the designation ОЦТГА-135 000/500 reads: single-phase, forced-oil and water cooled, triple-wound, lightning-protected, step-up autotransformer with a capacity of 135 000 kV A and a voltage of 500 kV on the HV side. The designation АТДЦТН-125 000/220 should be read as follows: step-down autotransformer, three-phase, forced-oil air-blast-cooled, triple-wound, with on-load tap changing, and with a capacity of 125 000 kVA and a voltage of 220 kV on the HV side. Nowadays, all transformers are provided with means of lightning protect-

ion, therefore the letter Г at the end of the letter designations of transformer types is omitted.

The list of letter designations given above is far from being complete, for all types of special-purpose transformers contain additional letters in their designations. For instance, transformers intended for use with arc furnaces are designated by the letter Э, those for application in conjunction with mercury-arc rectifiers, by the letter Р, and so on.

Until recently, Soviet transformer manufacturers put out Size I and II power transformers in a great variety of designs, which fact was testified to by the multiplicity of transformer type designations, such as ТМ, ТСМ, ТСМА, ТМА, ТАМ, and so on. In these designations, the letter С indicates the use in the transformers of cold-rolled steel, and the letter А, the use of aluminium winding wire. At present, in accordance with the new standards, the transformer-building works in this country have changed over to the manufacture of power transformers of these sizes in a single design version employing cold-rolled steel and aluminium winding wire. So, now we have a single type—ТМ—for all Size I and II power transformers and for some Size III transformers.

3.2. General Design of Transformers

A transformer consists of a core, coil (or windings), tapping switch, terminal bushings, leads, insulation system, tank, coolers, accessories, protective devices, and control and measuring instruments.

As the capacity and voltage class of the transformer grow higher, the structure of its components becomes more complex. Thus, for example, a simple single-phase arc-welding transformer for 220 V on the HV side and 60 V on the LV side has a frame-like two-limb core, windings, terminal board, and protective shell, but a high-capacity power transformer of Voltage Class, say, 110 kV is an electrical apparatus of a fairly complex construction. Special-purpose elements, such as on-load tap-changers, especially complicate the construction of a transformer.

Figure 3.1 shows a cut-away view of the ТМ-50/6 type three-phase oil-immersed transformer of Size I. The internal part of the transformer, which is placed inside a tank *1* and

consists of a core *14*, windings *8*, a tapping switch *10*, and leads *7* and *9*, is called the core coil assembly. When disassembling Size I through III transformers, the core-coil assemb-

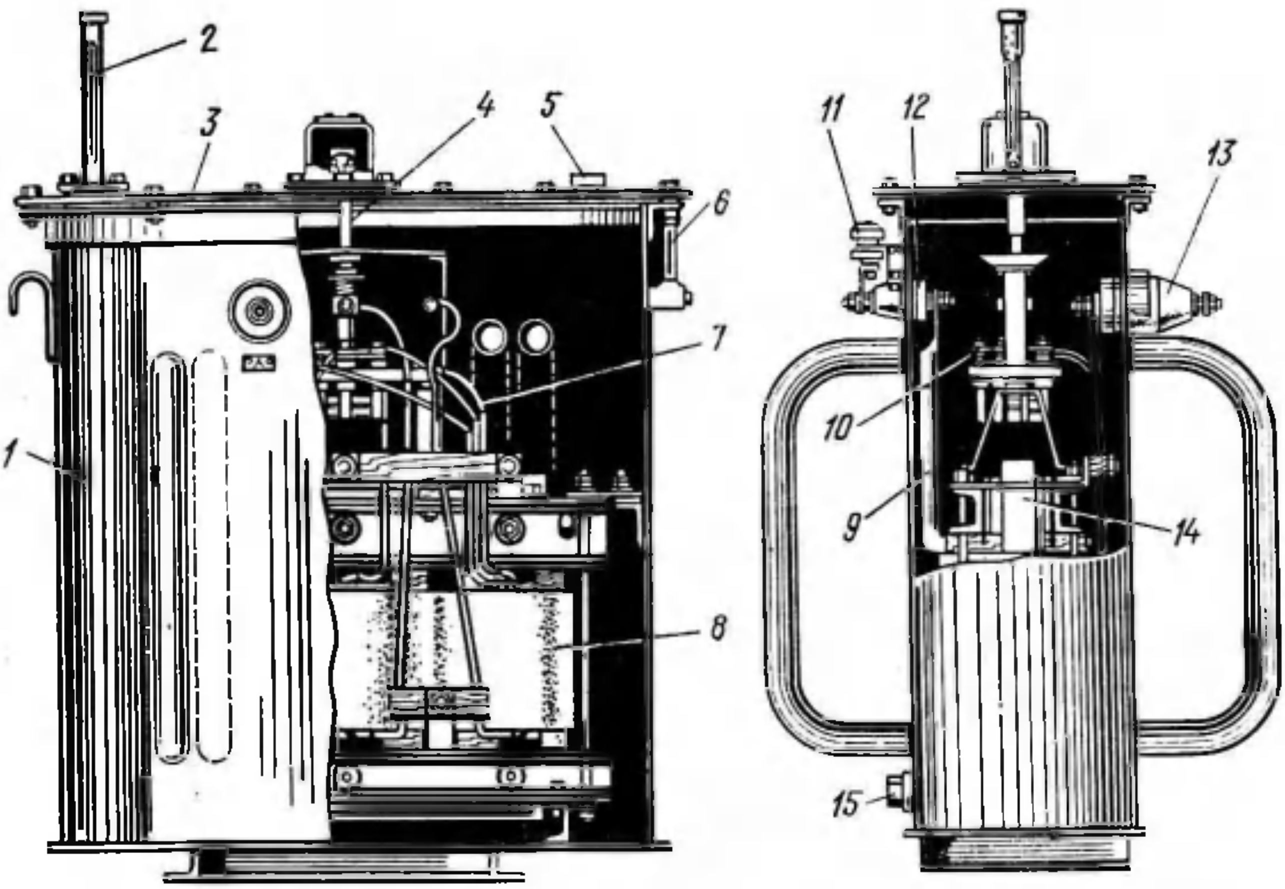


Fig. 3.1. Type TM-50/6 three-phase transformer for 6 000 ± 5%/400 V

1—tubular tank; *2*—thermometer; *3*—tank cover; *4*—tap-changer drive; *5*—oil-filler and air-bleed plug; *6*—oil gauge; *7*—HV leads; *8*—windings; *9*—LV leads; *10*—tap-changer; *11*—spark-gap protector; *12*—LV (400-V) terminal bushing; *13*—HV (6 000-V) terminal bushing; *14*—core; *15*—oil-sampler and drain plug

ly has to be removed from the tank, therefore, in practice, this part is frequently referred to as the withdrawable part.

Now we shall consider the structural components of a transformer in greater detail.

3.3. The Transformer Core

The transformer core is a closed magnetic circuit built up of thin laminations of electrical sheet steel. It is intended to concentrate the main magnetic flux linking with the windings, and consists of limbs which carry the windings and yokes which close the magnetic circuit. The core laminations are insulated from one another by a film of heat-resistant coating or varnish, or by a combination of both. There may

be two forms of magnetic circuit: the shell type and the core type.

A magnetic circuit of the *shell type* is branched: there are two yokes per limb, which encircle the limbs on both sides. As the magnetic flux leaves a limb, it branches off into two parts, therefore, in shell-type transformers, the cross-sectional area of the limbs is twice that of the yokes. The limbs and yokes are rectangular in section, which necessitates the use of rectangular disk windings. Because of the insufficient strength of such windings in the event of short circuits, complications in assembly, and also somewhat greater mass of the shell-type magnetic circuits as compared with the core-type circuits using cylindrical windings, the shell type in the Soviet Union is employed only for single-phase transformers in household appliances and for some special-purpose transformers.

The *core-type* magnetic circuits of butt-joint or interleaved (or imbricated) construction are used in power transformers. In such circuits, two or three (depending on the number of phases) vertical limbs are bridged over by two horizontal yokes—the top and the bottom one—so that a closed magnetic circuit is formed.

The core limbs and yokes are built up of separate laminations of electrical sheet steel 0.35 or 0.5 mm thick.

Limbs *1* (see Fig. 3.2) and yokes *3* and *5* are stacked up separately and then butt-joined and clamped with vertical tie-rods *4* to obtain a *butt-joint* core. Butt-joint cores are easy to assemble, but they suffer from a number of substantial drawbacks. At present, this type of core construction can be found only in old transformers and in some models manufactured in other countries.

Most power transformers made in the USSR are of the imbricated-core type. In such cores, the limb and yoke laminations are *interleaved* (see Fig. 3.3): in one layer, the short limb laminations are butt-joined with the long yoke laminations, and in the next layer, the long limb laminations are butt-joined with the short yoke laminations so as to overlap the joints between the laminations in the preceding layer. By stacking layers upon layers of such alternately arranged laminations, a core of the required thickness is obtained. Such an assembly of core laminations is called

interleaving with right-angled joints between the laminations.

To speed up the assembly, each layer is made two or three laminations thick. Accordingly, the assembly is called double-lamination interleaving or triple-lamination interleaving.

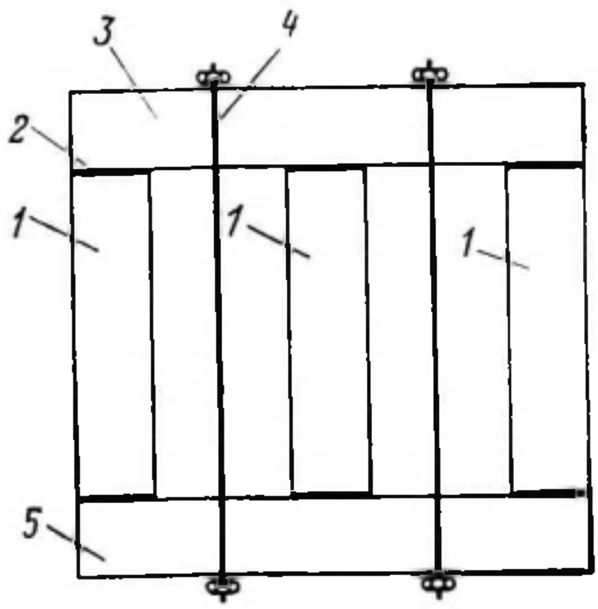


Fig. 3.2. Butt type of transformer core

1—core limbs; 2—insulating strip; 3—top yoke; 4—tie-rod; 5—bottom yoke

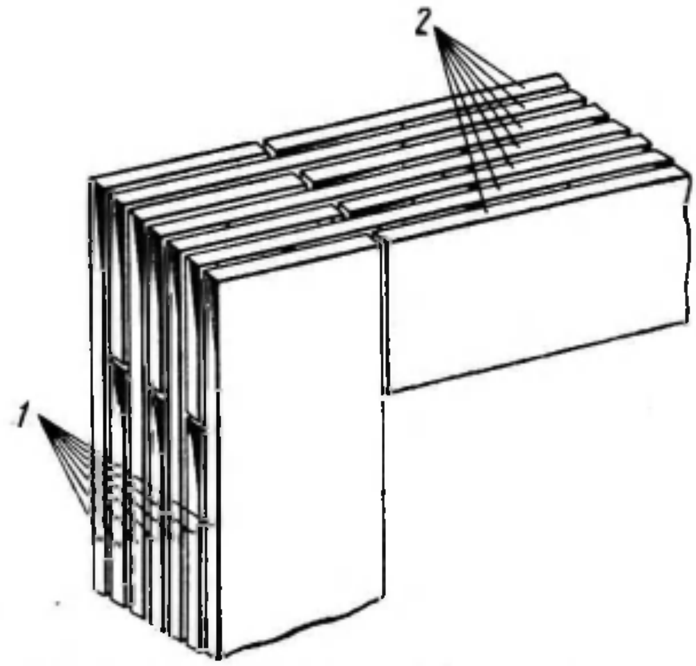


Fig. 3.3. Imbricated type of transformer core with right-angled joints

1—core laminations; 2—yoke laminations

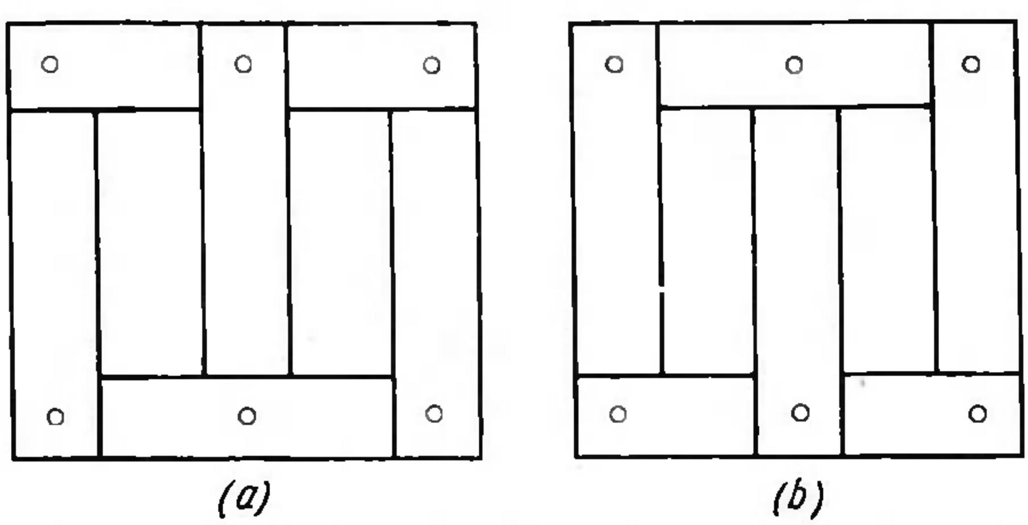


Fig. 3.4. Arrangement of laminations in an imbricated three-limb core with right-angled joints

(a) arrangement of laminations in one of the alternating layers; (b) arrangement of laminations in the next layer

The arrangement of laminations in the alternating layers of an imbricated three-limb core with right-angled joints between the laminations is shown in Fig. 3.4.

The interleaving with right-angled joints between laminations was widely used for cores made from hot-rolled steel. When using cold-rolled steel, to make the most of its properties, the cores are designed and assembled in such a way as to ensure that the lines of magnetic flux may coincide with the steel rolling direction not only in the core limbs and yokes, but also in places where they change their direction while passing from the limbs into yokes and vice versa (in Fig. 3.5, these areas are hatched). This is achieved by making use of bevelled (miter) joints between the limb and yoke laminations (see Fig. 3.6). The miter joints reduce the magnetic circuit areas where the lines of magnetic force do not coincide with the steel rolling direction. Moreover, they increase the length and hence, the area of the joint by a factor of $\sqrt{2}$, thus reducing the magnetic induction in the gap and consequently, the exciting current.

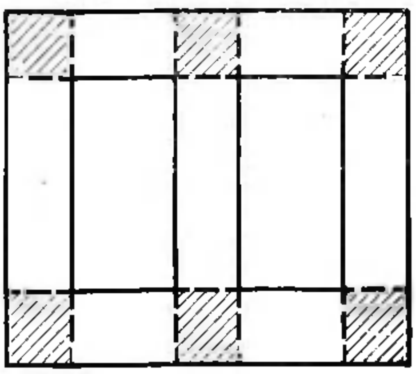
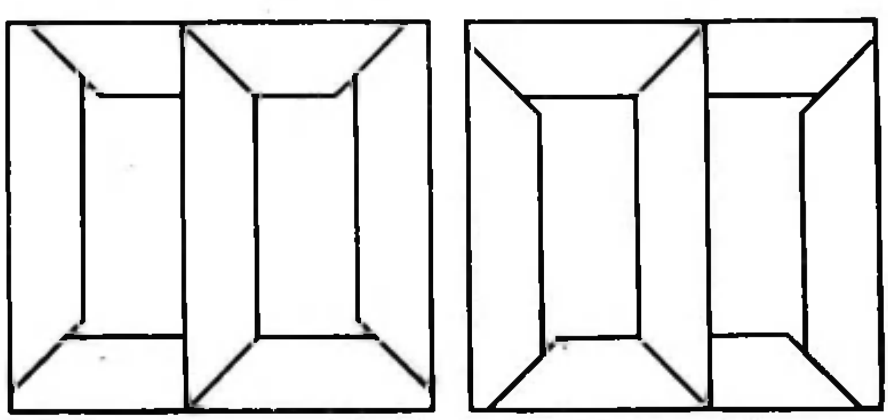


Fig. 3.5. Core areas (hatched) where the direction of the lines of magnetic flux does not coincide with the steel rolling direction

The use of interleaved cores with miter joints between aminations may reduce the no-load losses of transformers-



(a) (b)

Fig. 3.6. Arrangement of laminations in an imbricated three-limb core with bevelled (miter) joints

(*a*) arrangement of laminations in one layer; (*b*) arrangement of laminations in the next layer

by 10 to 12%, and the exciting current, by 25 to 30%. However, such joints complicate the fabrication of laminations

and the core assembly, therefore, resort is frequently made to some simplifications: imbricated cores are made with four miter joints (at the corners) and three right-angled joints, or a combined pattern is used wherein the miter joints at two corners of the core in one layer of laminations alternate with the right-angled joints in the next layer (see Fig. 3.7).

Size I and II transformers are also made with spatial rather than plane cores of butt-joint construction, which

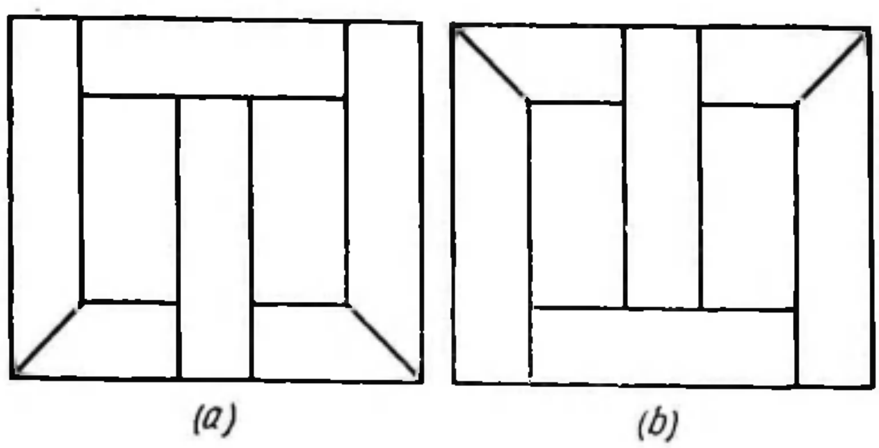


Fig. 3.7. Arrangement of laminations in an imbricated three-limb core with right-angled and miter joints

(a) arrangement of laminations in one layer; (b) arrangement of laminations in the next layer

are noted for the symmetrical arrangement of their limbs. Such cores consist of two triangular yokes wound from electrical steel strip or ribbon, between which there are three stepped-section limbs built up of laminations of the same length. The chief advantage of this core is its simple construction, which makes possible extensive mechanization and complete automation of production processes.

Size I transformers also use distributed, three-frame, wound magnetic circuits consisting of three O-shaped cores wound from electrical steel strip and arranged in space so as to form a trihedral prism. In such transformers, the windings are wound directly on the core limbs by passing wire through the openings in the adjacent O-shaped cores.

The limb and yoke sections are built up of a number of steps in order to make their shape approximate a circle (see Fig. 3.8). The steps are obtained by using laminations differing in width. In older transformer models, the yokes were made rectangular, T-shaped, or cross-shaped in section.

To obtain the required electromagnetic characteristics of the core and to make it mechanically strong, the core limbs and yokes are compressed (clamped) until the specified clamping tightness is attained. In transformers with a capacity of up to 630 kV A, the core limbs are not clamped, because they are sufficiently rigid to ensure stable vertical position of the core. When fitting windings on the core limbs of transformers with a capacity of 250 to 630 kV A, the limbs

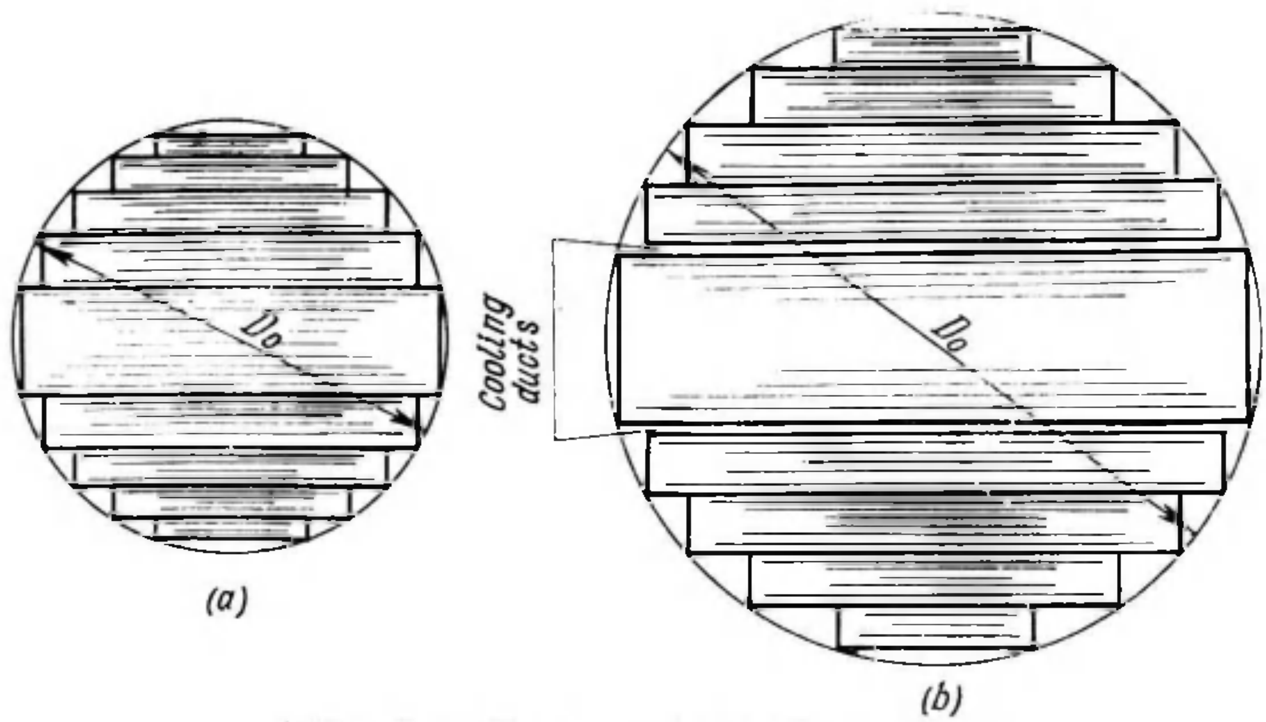


Fig. 3.8. Cross sections of core limbs

(a) in low-capacity transformers; (b) in high-capacity transformers; D_0—diameter of circumscribed circle

are temporarily compressed with screw clamps. After fitting the windings, the required clamping tightness of the core limbs is ensured by wedging them with beechwood blocks and cleats.

The clamping of transformer cores may be effected with or without through clamping studs. Clamping with through studs was widely used for cores made from hot-rolled steel. In this case, holes are punched in the limb and yoke laminations to fit the clamping studs after assembling the core. The studs are insulated from the active steel and from the yoke clamps by means of paper-base laminate tubes and insulating washers made either of pressboard or paper-base laminate. This method of clamping is illustrated in Fig. 3.9*a*. It is rather complicated and leads to an increase in the no-load losses.

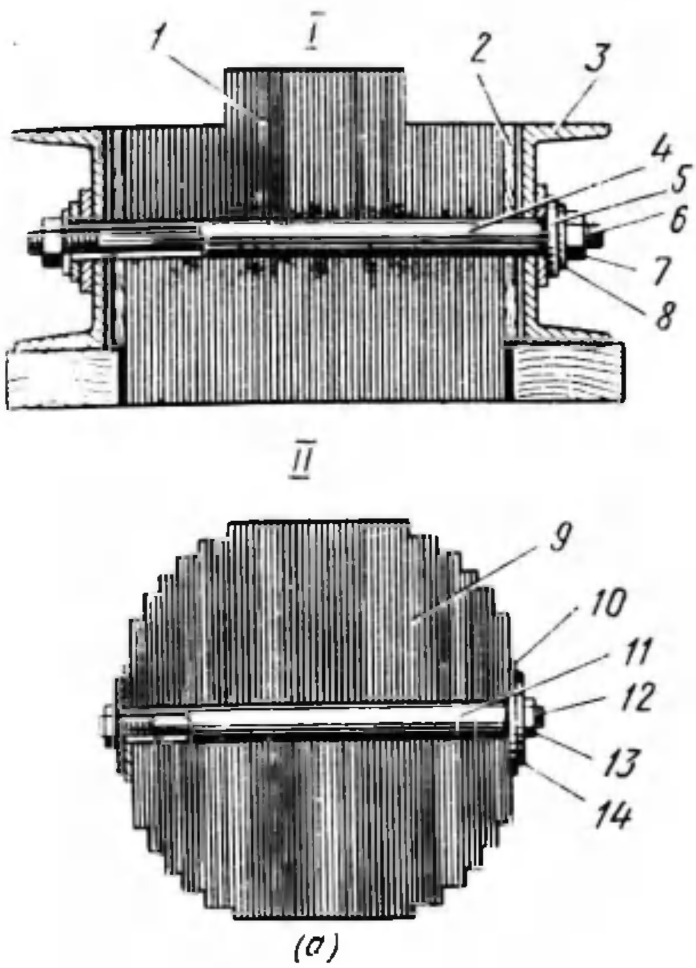
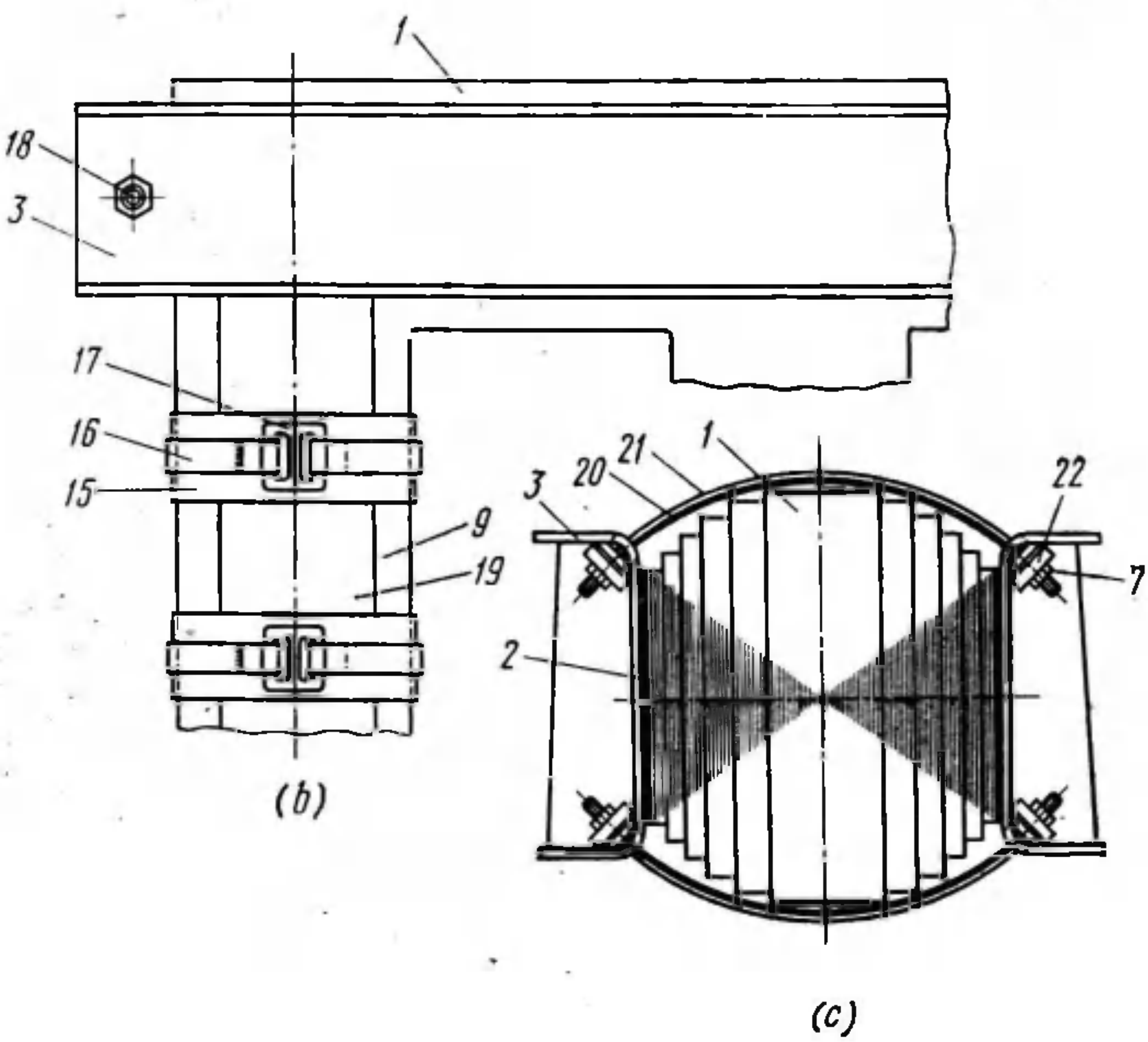


Fig. 3.9. Methods of clamping transformer cores

(*a*) clamping with through studs (*I*—clamping of a yoke; *II*—clamping of a core limb); (*b*) clamping with external studs and binding bands; (c) clamping with half-ring binding clips; *1*—yoke; *2*—pressboard insulation; *3*—yoke clamp; *4* and *11*—paper-base laminate tubes; *5* and *10*—insulating washers; *6* and *12*—through clamping studs; *7* and *13*—nuts; *8* and *14*—steel washers; *9*—core limb; *15*—pressboard insulation under binding bands; *16*—steel binding band; *17*—insulated buckle; *18*—external clamping stud; *19*—steel plate with hooks at the ends; *20*—pressboard insulation under half-ring binding clips; *21*—steel half-ring binding clip; *22*—insulating washer (glass-fabric-base laminate)



In cores made from cold-rolled steel, the limbs and yokes are exclusively clamped without making use of through studs. This method dispenses with the need for punching holes in the laminations and provides for better utilization of the properties of the cold-rolled electrical steel, since there are no holes in the laminations for the lines of magnetic force to by-pass and thus deviate from the steel rolling direction.

One of the methods of clamping transformer cores without through studs is illustrated in Fig. 3.9*b*. The yoke is clamped with yoke clamps *3* which are compressed by external clamping studs *18* installed at the ends of the clamps (outside the active core steel). In more powerful transformers, the yokes are additionally clamped with half-ring binding clips placed in the core windows, i.e., in spaces between the limbs (see Fig. 3.9*c*). Core limbs *9* are clamped with steel binding bands *16*. The number and arrangement of the binding bands are chosen so as to ensure that the clamping force is uniformly distributed along the laminations and the pressure between the laminations in the central packet is 4 to 6 kgf*/cm^2.

To prevent the binding band from forming a short-circuited turn, its ends are fastened by means of a buckle *17* provided with an insulating plastic coating. The band is insulated from the active steel of the core limb by means of 2 to 2.5 mm thick press-board insulation *15*.

The top and bottom yoke clamps are mechanically connected by means of steel plates *19* placed on both sides of each core limb. The plates have special hooks at their ends, which fit into holes provided in the yoke clamps. Vertical steel tie-rods may also be used for the purpose.

The metal binding bands are insufficiently reliable, because of the possibility of their forming a short-circuited turn as a result of damage to the insulating coat on the buckle. Besides, they cause additional losses, become loose when heated, and are difficult to fit and repair. Therefore, at present, they are replaced by glass binding tape Grade ЛСБТ. The binding tapes of certain definite thickness and width are applied onto the core limbs on a special machine,

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* In the SI system, the unit of force is the newton (N). 1 N = = 0.102 kgf.

the tape layers being cemented together during the operation to form a solid binding.

Nowadays, the yokes of transformers having a capacity of 4 000 to 6 300 kV A are clamped with external clamping studs, and the core limbs, with glass binding tapes. In more powerful transformers, the yokes are clamped with external

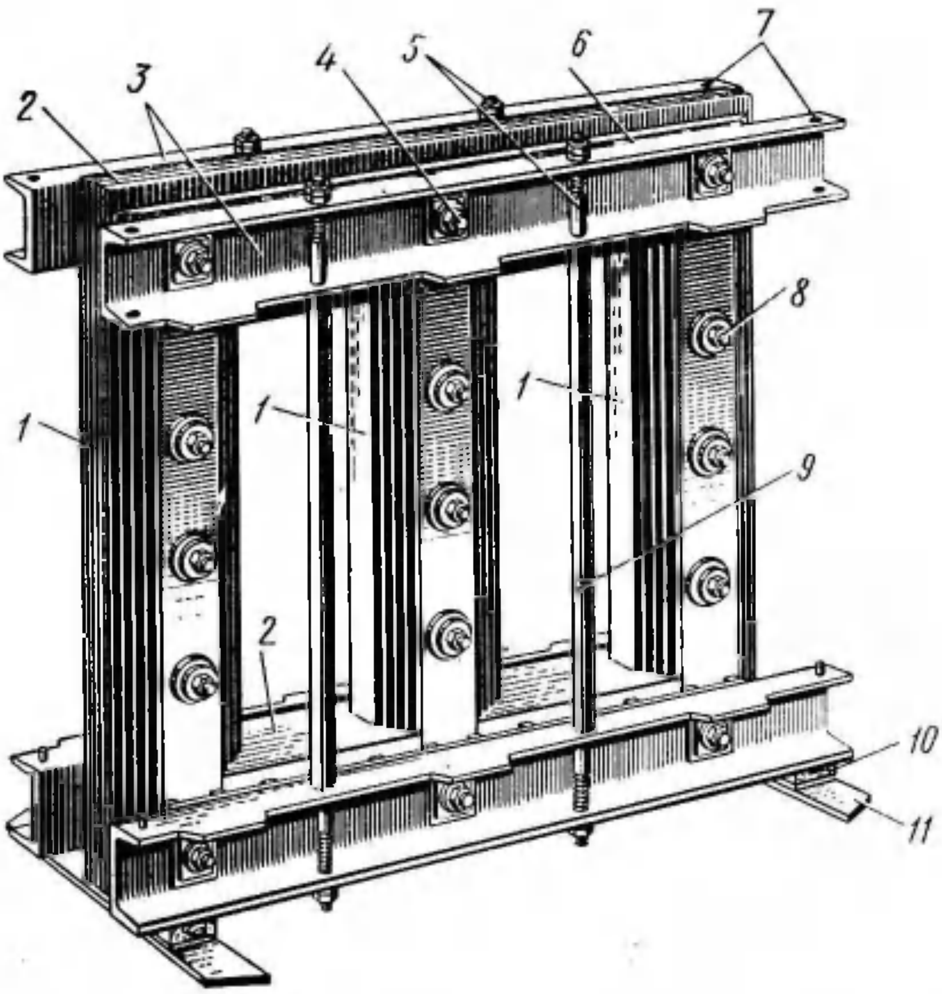


Fig. 3.10. Core of the Type TM-1800/35 three-phase transformer

steel "boxes" (insulated with pressboard) which abut against the extreme core limbs and half-ring binding clips placed in the core windows, and the core limbs are clamped with glass binding tapes.

Figure 3.10 shows the three-limb imbricated core of the TM-1800/35 type transformer using through core-clamping studs. Core limbs *1* and yokes *2* are built up of 0.5 mm thick hot-rolled steel laminations. Yoke clamps *3* and through clamping studs *4* (fitted at the points of intersection of the yoke and limb axes) serve for uniform and tight clamping of the yokes. In addition, the yoke clamps support the windings and take up the load from the lifting rods (not shown in the figure) which are fitted in holes *7* and serve for removing

the core-coil unit of the transformer from the tank. The yoke clamps are either made of channel iron or welded from separate steel strips, or else, formed from sheet steel.

The active core steel, yoke clamps, and studs are insulated from one another. The damaging of the insulation between these components may cause local overheating, increased losses, and failure of the transformer. The yoke clamps are insulated from the active core steel by means of pressboard strips *6*. The clamping studs *4* and *8*, which pass through the holes in the yokes and limbs, respectively, are insulated with paper-base laminate tubes and washers (see Fig. 3.9*a*).

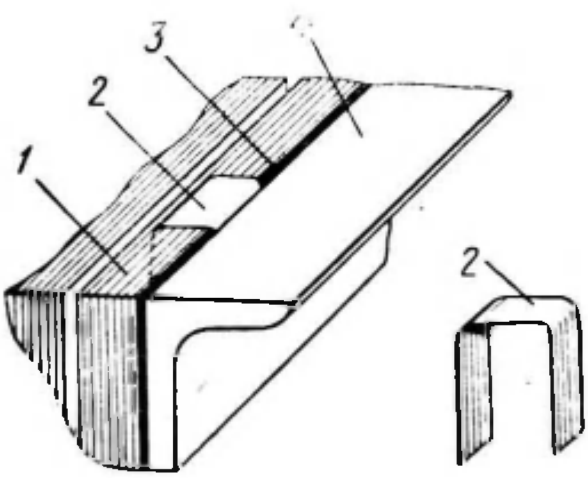


Fig. 3.11. Earthing of a transformer core

1—first core packet; *2*—earthing strip; *3*—insulating strip; *4*—yoke clamp on the LV side

The top and bottom yokes are mechanically connected by means of vertical tie-rods *5* inserted into paper-base laminate tubes *9*. At the same time, the tie-rods serve for the vertical clamping of the windings. Beechwood blocks *10* and steel strips *11*, which are secured to the bottom yoke clamps, form a support for installing the core-coil unit in the tank.

The heat liberated in the transformer core as a result of hysteresis and eddy-current losses has to be dissipated. In transformers with a capacity of up to 6 300 kV A, the external surface area of the core is usually sufficient for the purpose, but in more powerful transformers, the cooling surface area of the core has to be increased. This is done by forming longitudinal ducts in the active steel. Similar ducts are formed between the yokes and yoke clamps by fitting vertical pressboard strips onto the insulating strips *6*.

During operation, the core and other metal components of the transformer are subjected to a strong electric field, as a consequence of which they become charged. Since individual components are charged differently, there is a potential difference between them, which may cause sparking. To prevent this, the core and the yoke clamps are earthed: a tinned copper strip *2* (see Fig. 3.11) is inserted to a depth

of 50 to 60 mm between the laminations of the first yoke packet *1* at a distance of 15 to 20 mm from the yoke clamp and then the other end of the strip is clamped between a yoke clamp *4* and an insulating strip *3*; the earthing circuit is completed to the earthed tank of the transformer either

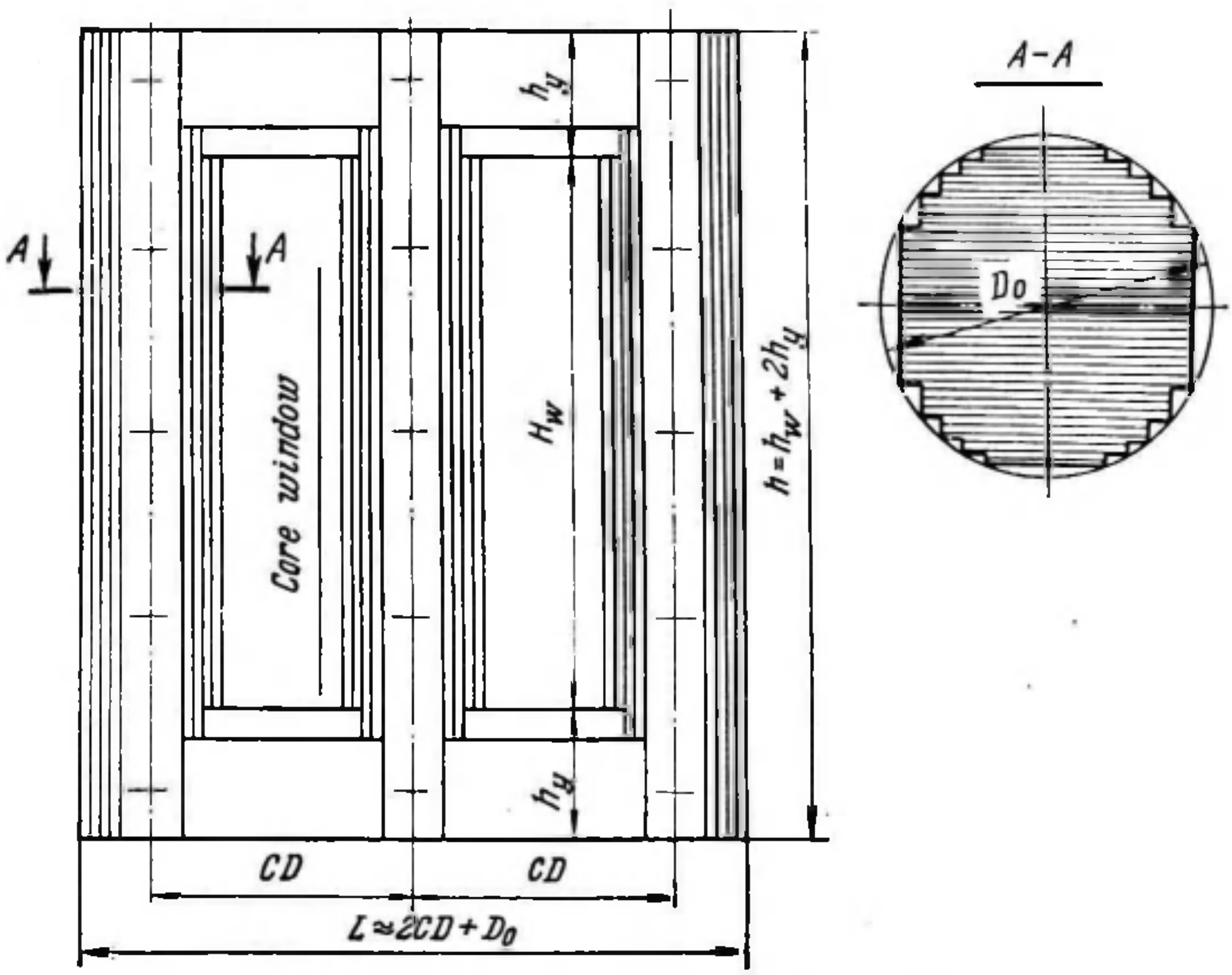


Fig. 3.12. Basic core dimensions

through special earthing connections inside the tank or through lifting rods. The earthing strip is fitted in the middle of the top yoke on the LV lead side.

When repairing a transformer, one frequently has to draw a sketch of the transformer core (see Fig. 3.12), showing the main core dimensions (*CD*—centre distance between the core limbs; H_w—window height; D_0—diameter of the circumscribed circle of the limb; h_y—yoke height; h—core height; L—core length), and to calculate the cross-sectional area of the active steel (less the lamination insulation) in the core limbs and yokes. All linear dimensions in the sketch should be given in millimetres, and the active steel section, in square centimetres.

3.4. The Windings

The windings of Size III through VII oil-immersed power transformers are wound mainly with Grade ПБ copper winding wire, and those of Size I and II transformers, with aluminium winding wire Grade АПБ. In dry-type transformers, the windings are wound with Grade ПСД wire insulated with two layers of glass fibre impregnated with a heat-resistant varnish. The insulation thickness of winding wire is customarily specified in terms of the diametral thickness. It is selected to suit the voltage class of the given transformer: 0.45 mm for voltages up to 35 kV, from 1.35 to 2 mm for 110 kV, and greater still for higher voltages. The insulation thickness of Grade ПСД wire is 0.27 to 0.4 mm.

Besides the wire, winding structures include various insulation components.

Transformer windings differ from one another in type, number of turns, wire grade and gauge, hand, creepage distances, and interturn insulation thickness. The higher the voltage of the transformer, the greater the number of turns in its windings, and the higher its capacity, the heavier the wire gauge and the greater the size of the windings. The current density in the windings, calculated on the basis of temperature rise, ranges from 2.5 to 4.5 A/mm^2, depending on the capacity and design of the transformer.

One must strictly distinguish between right- and left-hand windings. The hand of single-layer windings (Fig. 3.13*a*) is determined by the direction in which their turns have been wound during manufacture, no matter which of their ends (upper or lower) is considered the start. In multiple-layer windings wound with the same conductor passing from one layer into another without interruption (Fig. 3.13*b*), the hand alternates from layer to layer. The hand of such windings is considered to be that of the layer whose entrance end is taken as the start of the winding.

Disk windings made in the form of flat spiral coils (Fig. 3.13*c*) are considered left- or right-hand, according as their back or front end is taken to be the start. From the figure it is clear that if the front ends of such windings are considered the start, the first winding (the one on the left) will then be right-hand, and the second (on the right) will

be left-hand. Now, if we consider the back ends of the coils to be the start of the windings, their hand will then change to the left and right, respectively. If a disk coil is turned upside down, its hand will be reversed: a left-hand coil will become right-hand, and a right-hand one will become left-hand.

Disk coils are usually arranged in pairs (Fig. 3.13*d*). In this case, the front ends of the coils are the entrance ones,

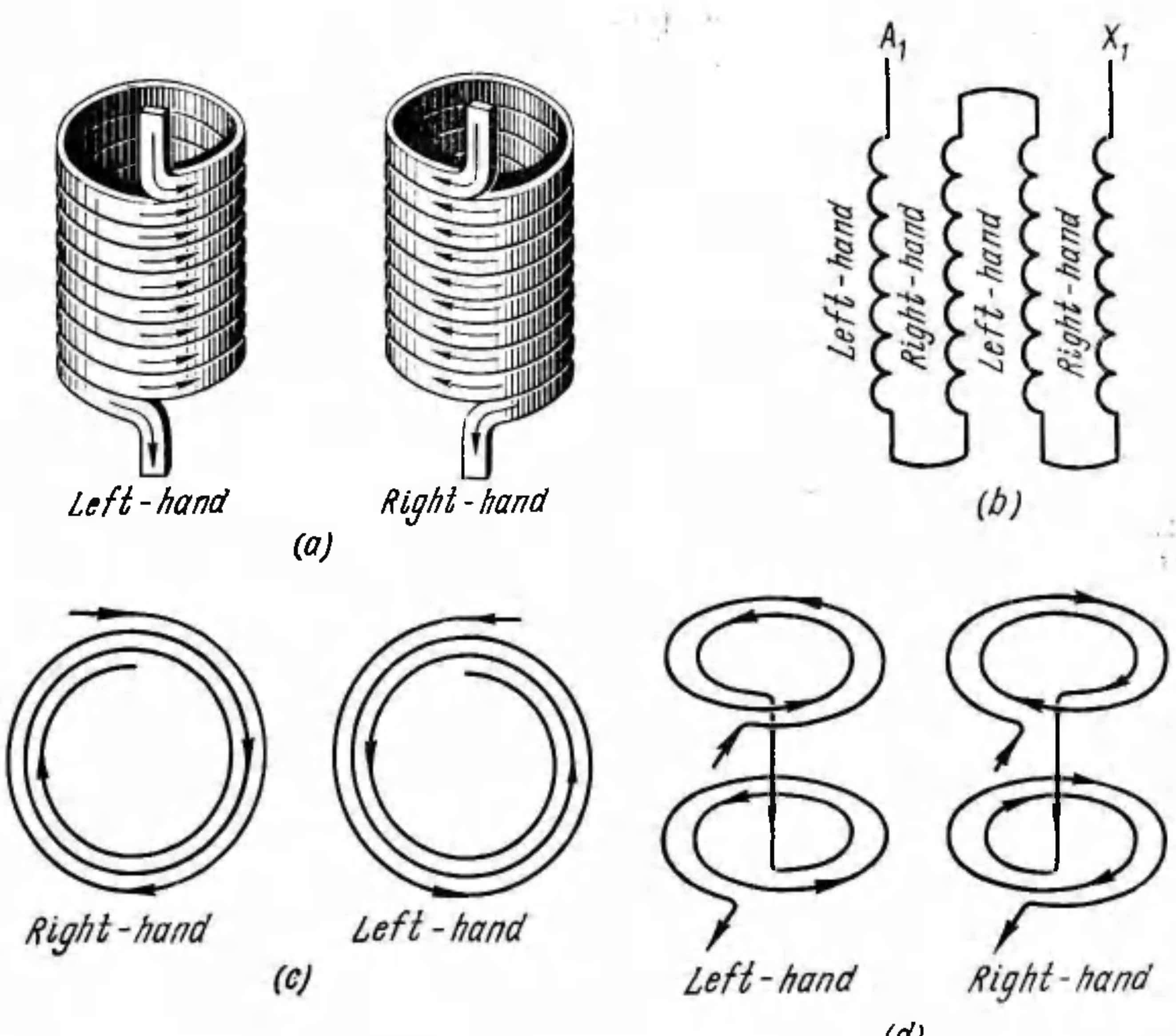


Fig. 3.13. Left- and right-hand windings

(*a*) single-layer; (*b*) multiple-layer; (c) single disk (flat spiral) coils; (*d*) paired disk coils

and the interdisk connection is made at the back. Here, the winding hand remains strictly defined, and a winding consisting of any number of paired coils of the same hand in series will have the same hand as the separate paired coils.

To give them mechanical strength and improve their moisture resistance, the windings are dried and then impregnated with Grade МЛ-92 or ГФ-95 varnish and baked in an oven at 100 to 110°C. Recent advances in the design, manufacture, and assembly of transformer windings have made it possible to dispense with the winding impregnation and baking. This materially cuts down the cost of the windings and clears production space. For the last few years, almost all transformer-building works and repair plants in the USSR have abandoned the practice of impregnating and baking the windings for transformers of Size III and upwards.

The LV and HV windings are arranged on the core limbs concentrically: the LV windings are placed on the inside and the HV ones, on the outside (in some special transformers, the LV and HV windings are arranged the other way round). The windings are separated by insulating cylinders.

The following types of transformer windings are most widely used in the USSR and other countries: single-, double-, and multiple-layer cylindrical windings, multiple-layer bobbin windings, continuous-disk windings, helical and pancake windings.

Single-Layer Cylindrical Winding

This winding has a single layer of touching turns wound helically with a single or several parallel conductors, usually rectangular in section. The start and finish of the single-layer winding are at the opposite ends. Due to the conductor width, the turns have a pronounced rake, therefore, to produce a trully cylindrical coil with horizontal end faces, edge-blocks are taped to the first and last turn of the winding. The edge-block is a split ring cut from a paper-base laminate cylinder or coiled from a wedge made up of several layers of pressboard taped together.

To make the winding stronger mechanically, the edge-blocks together with the extreme turns of the coil are wrapped with surgical tape wound half-lap.

The coil is wound on a template, or on a paper-base laminate cylinder which in this case doubles as the former of the winding and insulation between the winding and the core limb.

Single-layer cylindrical windings are used on the LV side of low-capacity single- and three-phase transformers. The winding shown in Fig. 3.14 has eight turns and is wound with two parallel conductors *1* per turn. Edge-blocks *2* are taped (not shown in the figure) to the first and last turn of

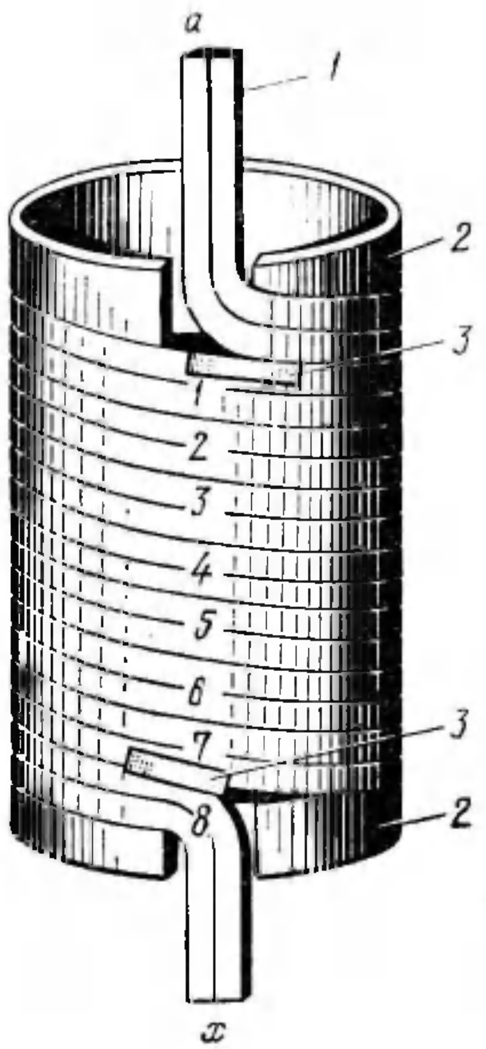


Fig. 3.14. Singe-layer cylindrical winding wound with two parallel conductors

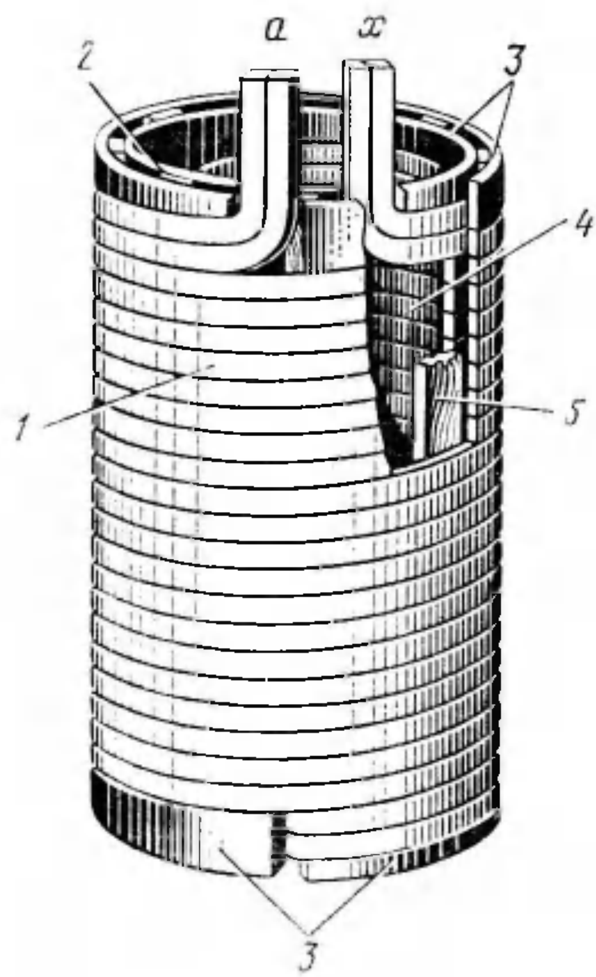


Fig. 3.15. Double-layer cylindrical winding wound with two parallel conductors

the coil. To improve the interturn insulation at places where the conductors are bent, use is made of U-shaped "boxes" *3* made from 0.5 mm thick pressboard. The boxes are fixed to the conductors with linen-finished tape wound half-lap in a single layer.

Double-Layer Cylindrical Winding

The winding has two layers of turns wound with a rectangular (strip) conductor, usually grade ПБ or АПБ. The turns in each layer, like those of the single-layer winding,

are wound touching and along a helical line, and there may be a single or several parallel conductors per turn.

Figure 3.15 illustrates a double-layer cylindrical winding wound with two parallel conductors per turn. Layer *1* is at the front of the coil, and layer *4*, at the back. The conductors pass from one layer into the other at the bottom of the coil. Vertical cooling (oil) ducts *2* are formed between the layers by means of beechwood bars *5* and pressboard strips. These ducts serve to increase the cooling surface area of the winding. Paper-base laminate edge-blocks *3* are used to give a trully cylindrical shape to the coil.

In such windings, the conductors are generally wound on the flat, but may also be wound on the edge. As a rule, the parallel conductors have the same size and shape in section. The interturn insulation at places where the conductors are bent is strengthened by means of pressboard boxes. The start *a* and finish *x* of the winding are arranged at the top of the coil. With this marking of the coil ends, the winding will be right-hand.

Like the single-layer winding, the double-layer winding is mainly used in the LV coils of transformers with a capacity from 40 to 630 kV A for voltages up to 525 kV.

Multiple-Layer Cylindrical Winding

This type is wound with round-wire conductors Grade ПБ or АПБ (except for the aluminium-wire windings of transformers with a capacity of 400 kV A and upwards for voltages up to 6 kV, which generally use rectangular conductor Grade АПБ). The former of the winding is a paper-base laminate cylinder *1* (see Fig. 3.16*a*). The first winding layer is wound on the former, while each subsequent layer, on a paper cylinder *2* formed by several layers of cable paper wrapped around the preceding coil layer and serving as interlayer insulation. The interlayer insulation cylinders project beyond the coil layers, and the spaces between them are filled with 1 to 1.5 mm thick and 12 mm wide pressboard strips *5* (see Fig. 3.16*b*) cemented vertically onto cable or telephone-cable paper 60 to 80 mm wide, so that stiff edges are formed on the coil.

Where the cooling surface area of the winding has to be increased, the winding is divided into two concentric coils separated by vertical ducts *3* (see Fig. 3.16*a*) which are formed by vertical bars *4* placed at about one-third of the winding's thickness from cylinder *1*. At voltages from 6 to 10 kV, these bars are frequently made of beechwood, while at 35 kV, they are made up of adhesive-bonded pressboard strips.

Figure 3.16*c* shows a schematic diagram of a simple multiple-layer cylindrical winding having three voltage-control

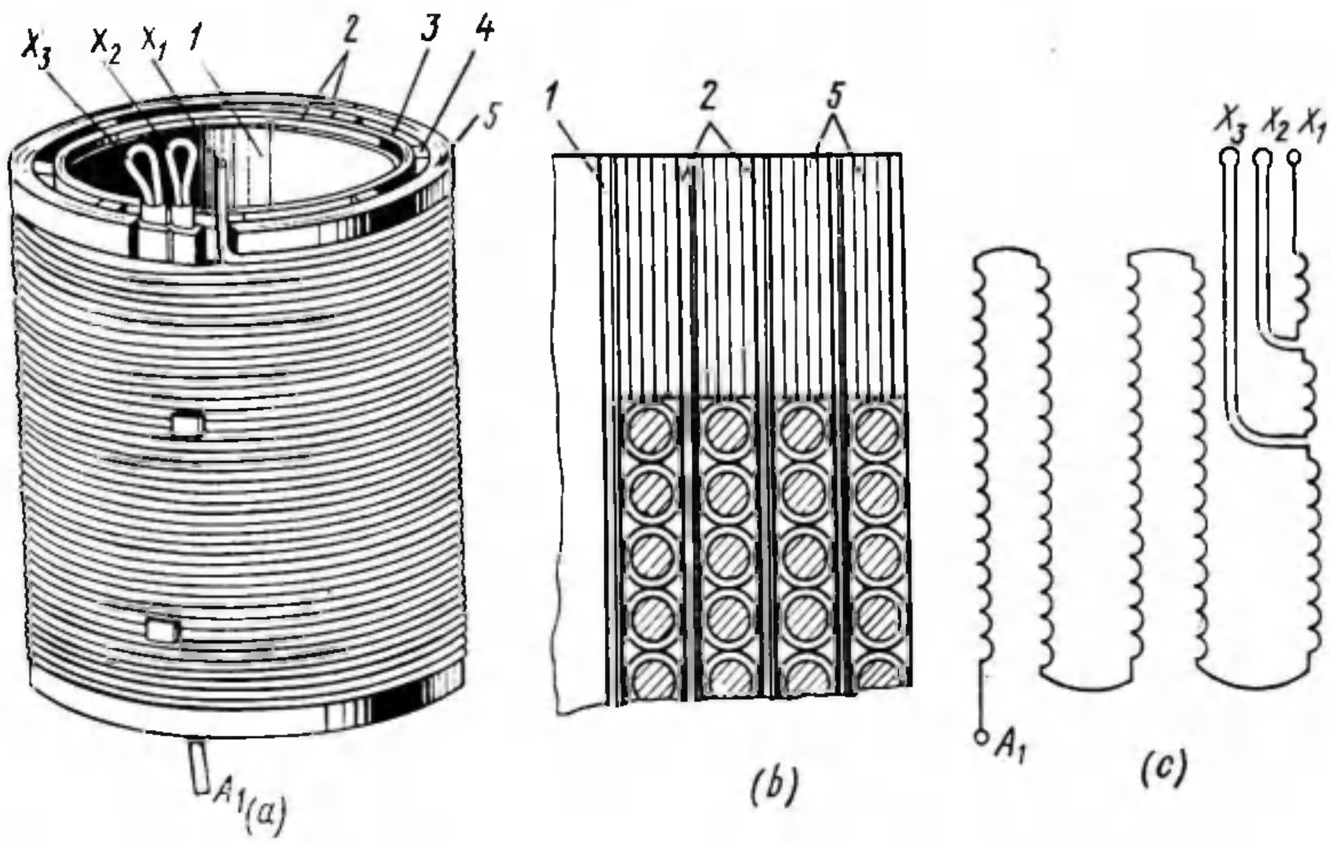


Fig. 3.16. Multiple-layer cylindrical winding

(*a*) external view; (*b*) insulation at the end of the coil; (*c*) diagram of a simple winding with three voltage-control taps

taps (X_1, X_2, and X_3) arranged at the neutral end of the winding. The taps are made in the form of loops of the same wire as the winding itself, and are insulated with either cable-paper tubes or fabric sleeves, or else with crepe paper and linen-finished tape. Pressboard strips 0.5 mm thick are placed both under and over the taps X_2 and X_3. To give mechanical strength to the winding, the extreme turns are fastened with loops of cotton tape, and the whole winding is then wrapped over its entire height with surgical or linen-finished

tape wound in the direction of the winding turns, impregnated with glyptal varnish, and baked.

The main disadvantage of this type of multiple-layer winding is the asymmetrical arrangement of the regulating turns with respect to the mid-height of the winding. This asymmetry causes dangerous mechanical forces to act upon some of the winding turns in the event of a short circuit. Lately, a magnetically symmetric arrangement with five voltage-control taps has found application for multiple-layer cylindrical windings. Such a winding is shown schematically in Fig. 3.17. Here, the taps are taken from one or two outermost layers. Each voltage-control step is divided into two symmetrical groups of turns (*C1* and *C2*) connected in series. At the first tap, the entire tapped layer of the winding is in circuit; at the second tap, the two central groups are disconnected; at the third tap, another two groups arranged next to the central ones and symmetrically about the coil ends are brought out of circuit; at the fourth tap, two more groups arranged next to the last groups at the ends of the coil are disconnected; and at the fifth tap, the entire tapped layer is de-energized.

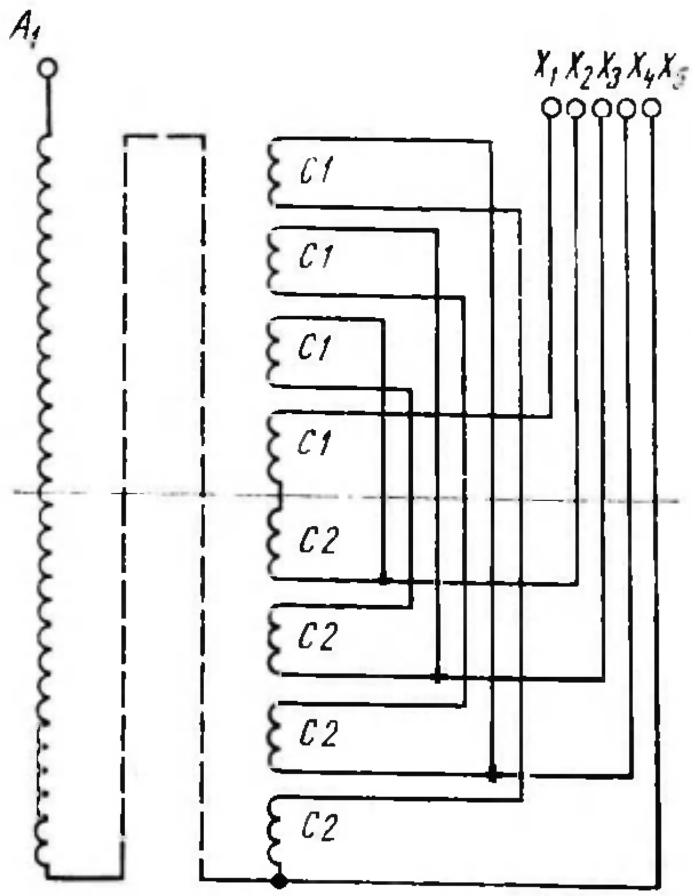


Fig. 3.17. Magnetically symmetric arrangement of a multiple-layer winding with five voltage-control taps

Multiple-layer cylindrical windings are mainly used as HV coils in transformers with a capacity of up to 630 kV A for voltages from 3 to 35 kV. A single three-phase tapping switch is used with the winding arrangements shown in Fig. 3.16*c* and 3.17.

Continuous-Disk Winding

This consists of several series-connected flat coils or disks *1* of the same radial size (Fig. 3.18). The disks are placed one above another, with horizontal cooling ducts *2* formed be-

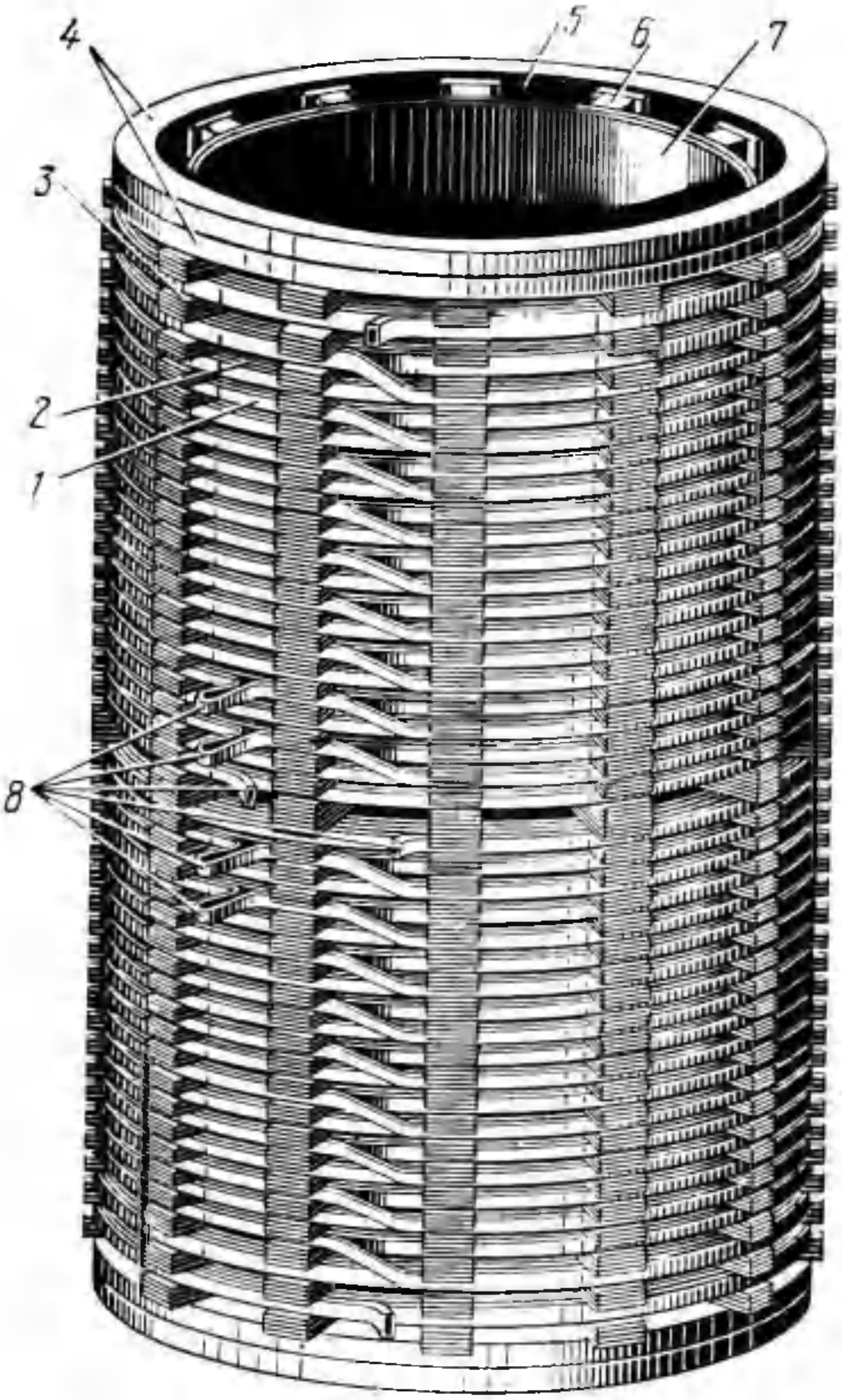


Fig. 3.18. Continuous-disk winding

tween them by pressboard spacing blocks *3*. Each disk is wound with a strip conductor (usually Grade ПБ or АПБ) on the flat and may have several turns touching in the radial direction.

Each turn of the disk may be wound with a single or several parallel conductors. The disks in the winding shown in Fig. 3.18 are wound with a single conductor per turn, and there are six voltage-control taps *8* arranged in the middle of the winding.

This type has been termed "continuous-disk", because a special winding technique is used to make the conductor pass from disk to disk without a single break in its continuity.

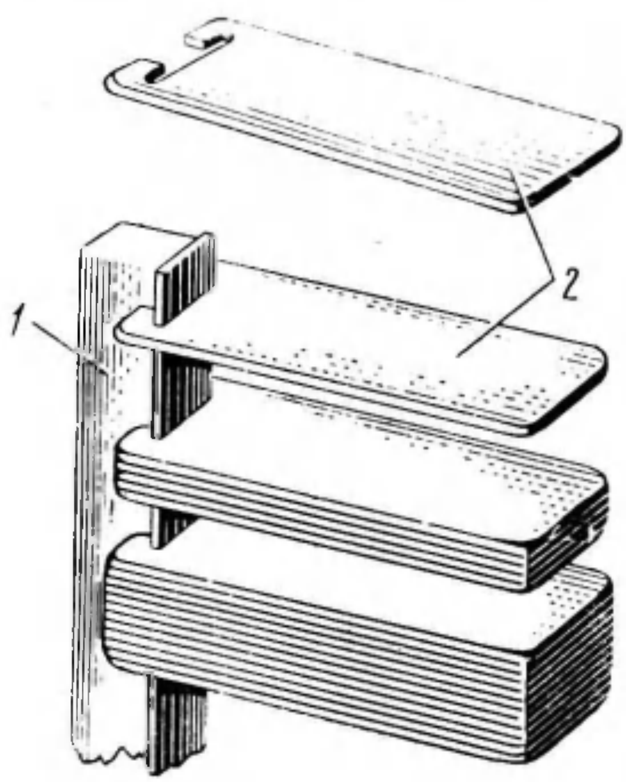


Fig. 3.19. Insulating components for forming ducts in continuous-disk windings
1—bar; 2—strip

The winding is wound around wooden bars *6* placed axially all the way round the periphery of a paper-base laminate cylinder *7* at regular intervals, so that vertical cooling ducts *5* are formed between the winding and the cylinder. Support insulation rings *4* provide reliable bearing surfaces for the winding.

In Size IV transformers, continuous-disk windings, as a rule, have no paper-base laminate cylinders. They are wound around wooden bars placed on a special metal cylinder (template) which is removed after the winding is completed. The cylinders (formers) for such windings are made from pressboard blanks immediately before fitting the winding on the core limbs. Insulation components are made of pressboard sheets. The horizontal ducts between the disks are formed by spacing blocks stacked up from separate pressboard strips *2* on bars *1*, as shown in Fig. 3.19. If the windings are not impregnated, their mechanical strength is improved by means of pressboard bars passed through dovetail recesses in the strips at the front of the coils.

Continuous-disk windings for voltages up to 35 kV are made from conductors with a two-side insulation thickness from 0.45 to 0.55 mm, and those for 110 kV use conductors with 1.2 to 1.35 mm thick insulation. In 110-kV windings,

the entrance or line-end coils, i.e., the two first and two last disks, are wound with conductors of increased insulation thickness in order to improve their electric strength. This impairs the cooling of these disks, so one has to take a heavier conductor for them. The disks are wound separately in pairs and then soldered in series with the disks in the main part of the winding. The number of disks in the winding is always even, therefore its start and finish are always at the back or the front of the extreme disks. In the former

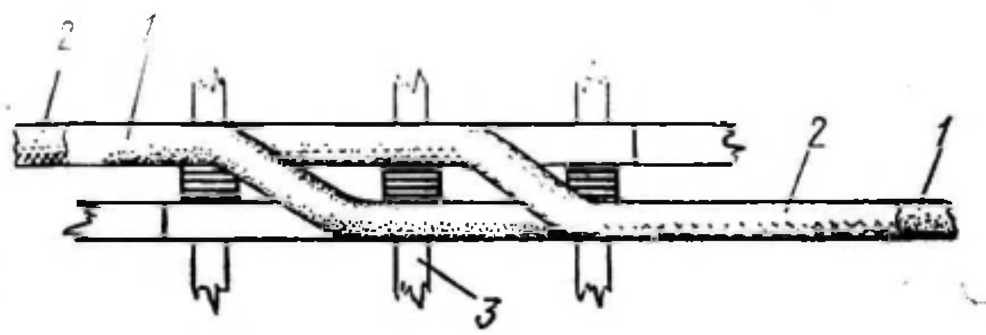


Fig. 3.20. Transposition of conductors

1—conductor passing from the front of the coil to the back; 2—conductor passing from the back of the coil to the front; 3—strip

case, the entrance disks are not reversed when making the winding, while in the latter case, they have to be reversed.

The interdisk connections in continuous-disk windings are made in free spaces between the spacing blocks. Here, the conductor is bent on the edge and reinforced with a pressboard box taped to it, or a special pressboard strip is placed under the bent conductor.

In cases where the windings are wound with several parallel conductors per turn, the conductors arranged farther from the coil axis will have a greater length than those closer to the axis. To equalize the lengths and consequently, the resistances of the parallel conductors, they are transposed so that each conductor may take each possible position when passing from disk to disk, as shown in Fig. 3.20. This makes for uniform distribution of current among the parallel conductors and, also, reduces the losses due to circulating currents caused by stray fluxes.

Parallel conductors reduce eddy-current losses in the winding copper and facilitate the winding of the disks, because several light-gauge conductors are used in place of a single heavy one.

Continuous-disk windings are solid and mechanically strong. They find application in LV, MV, and HV coils. The MV and HV coils are usually tapped in accordance with the direct and reverse tapped-winding arrangements.

As distinct from the windings for up to 35 kV, those of the 110-kV class and upwards include some special structural components serving the purpose of capacitive protection. Such a protection is necessary, because there is always a possibility that the transformer may be subjected to dangerous overvoltages likely to cause damage to its insulation.

High-frequency pulses of large amplitude and short duration, which arise in power transmission lines as a result of lightning discharges, propagate as waves along the lines at a speed close to that of light. For the oncoming high-frequency wave with a steep front, the transformer may be regarded as a capacitor, for at high frequencies the inductive reactance of the transformer grows materially and its individual winding elements (disks) become as if disconnected from one another; the disks then begin to act like the plates of distributed capacitors.

When the oncoming wave reaches the transformer, its input capacitance charges in a few fractions of a microsecond, and the surge voltage impressed on the entrance coils first drops to zero and then sharply rises, this setting up electromagnetic oscillations in the transformer windings, which depend on the winding inductance, capacitance, and resistance. In the transformer there sets in a process of transition from the initial, nonsteady distribution of voltage over the windings to the final, steady-state voltage distribution. In the course of this process, potential differences tens of times in excess of normal may develop between the winding disks, and still greater ones between the turns. The reason for this is the extremely nonuniform distribution of electric charge over the windings, stemming from the presence of distributed capacitances (between the winding disks, and between the disks and earthed parts, such as the core, tank, etc.) that disturb the uniformity of electric field. Here, the line-end turns and coils are most liable to insulation breakdown.

To make the initial distribution of potential over the entrance parts of the windings more uniform and to bring it

closer to the final, steady-state distribution, use is made of capacitance-grading rings. These rings increase the input capacitance of the windings and equalize the electric field of the line-end coils and turns, thus reducing voltage gradients across them. The capacitance-grading rings are electrically connected to the line ends of the coils and are reliably insulated from the earthed parts of the transformer.

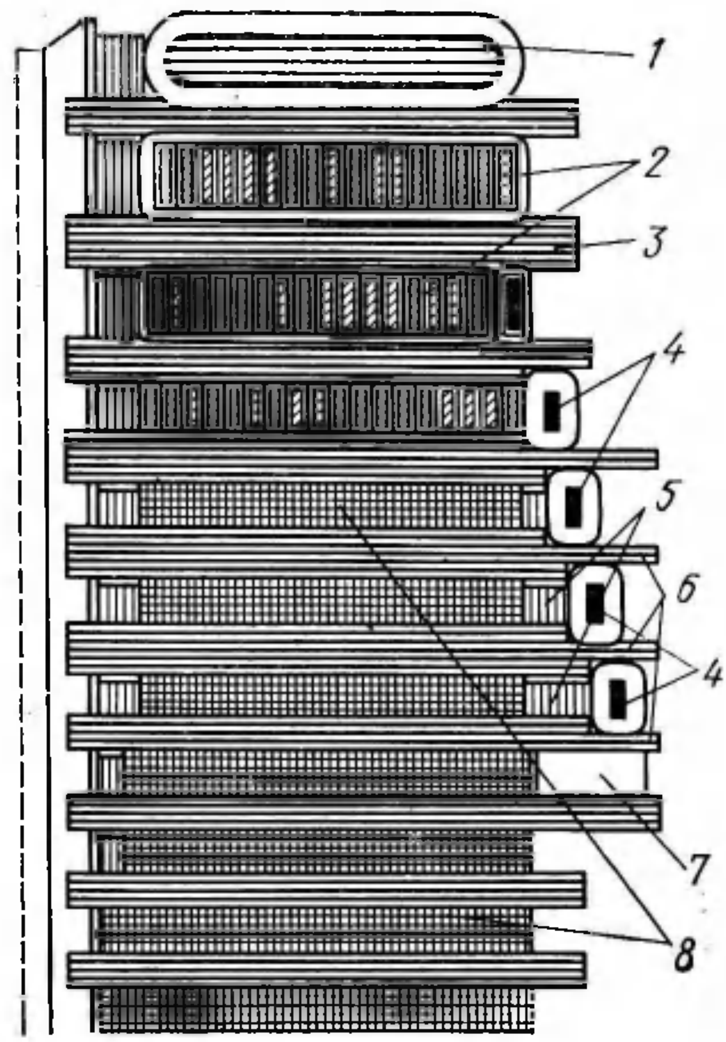


Fig. 3.21. Arrangement of a capacitance-grading ring and shielding turns (electrostatic shields) on a winding

1—capacitance-grading ring; *2*—line-end disk coils with additional insulation; *3*—spacers; *4*—shielding turns; *5*—pressboard strips; *6*—projecting ends of elongated spacers; *7*—supporting segment of pressboard; *8*—continuous-disk winding

The initial and final distribution of voltage over the entrance parts of the windings are equalized by means of electrostatic shields made in the form of open shielding turns encircling the five entrance coils and electrically connected to the capacitance-grading rings and line ends of the windings.

Figure 3.21 shows the arrangement of the capacitance-grading ring and shielding turns on a winding. The grading ring *1* is pressed from several pressboard washers, and is wrapped half-lap with a bare copper ribbon (foil). A portion of the ring 60 to 70 mm long is left unwrapped in order to

avoid the formation of a closed turn. Cable-paper insulation 4 to 5 mm thick (on one side) is applied over the copper ribbon. Shielding turns *4* are made from the same conductor as is used for the coils. The turns are additionally insulated with cable paper (one-side insulation thickness from 4 to 5 mm).

The arrangement of the shielding turns on the windings of a three-phase transformer is shown schematically in

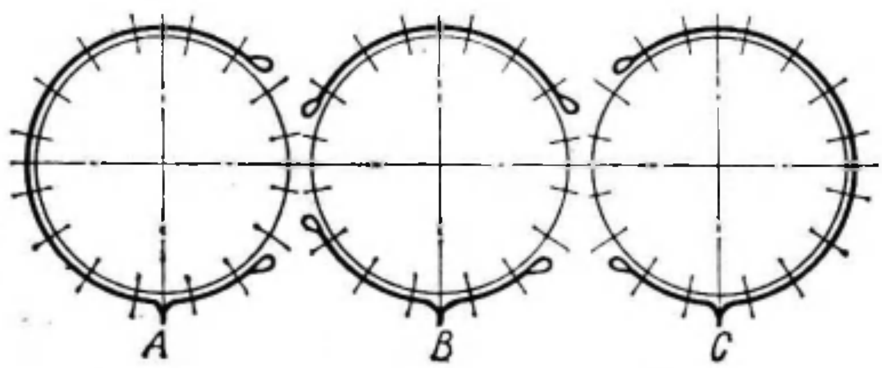


Fig. 3.22. Arrangement (in plan) of shielding turns on the windings of a three-phase transformer for 110 kV

Fig. 3.22. The electrical connection between the shielding turns, capacitance-grading ring, and line end of a winding is made in the form of a comb. The latest transformers for 110 and 220 kV have no shielding turns, but are provided instead with two grading rings per winding, one of them being arranged as shown in Fig. 3.21 and the other, placed between the second and the third coil.

Helical Winding

In this winding, the turns follow a helical line, each turn consisting of several parallel strip conductors touching in the radial direction (such a winding is sometimes referred to as the spiral winding).

Figure 3.23 shows a singly re-entrant helical winding wound with eight parallel conductors per turn. The insulation components of this winding are chiefly the same as in the continuous-disk winding. Spacers *7* between the turns form horizontal oil ducts, while bars *4* form vertical ducts between the winding and cylinder *5*.

Helical windings for Size I and II transformers are wound around wooden bars placed on paper-base laminate cylinders, while those for bigger units, around bars arranged on

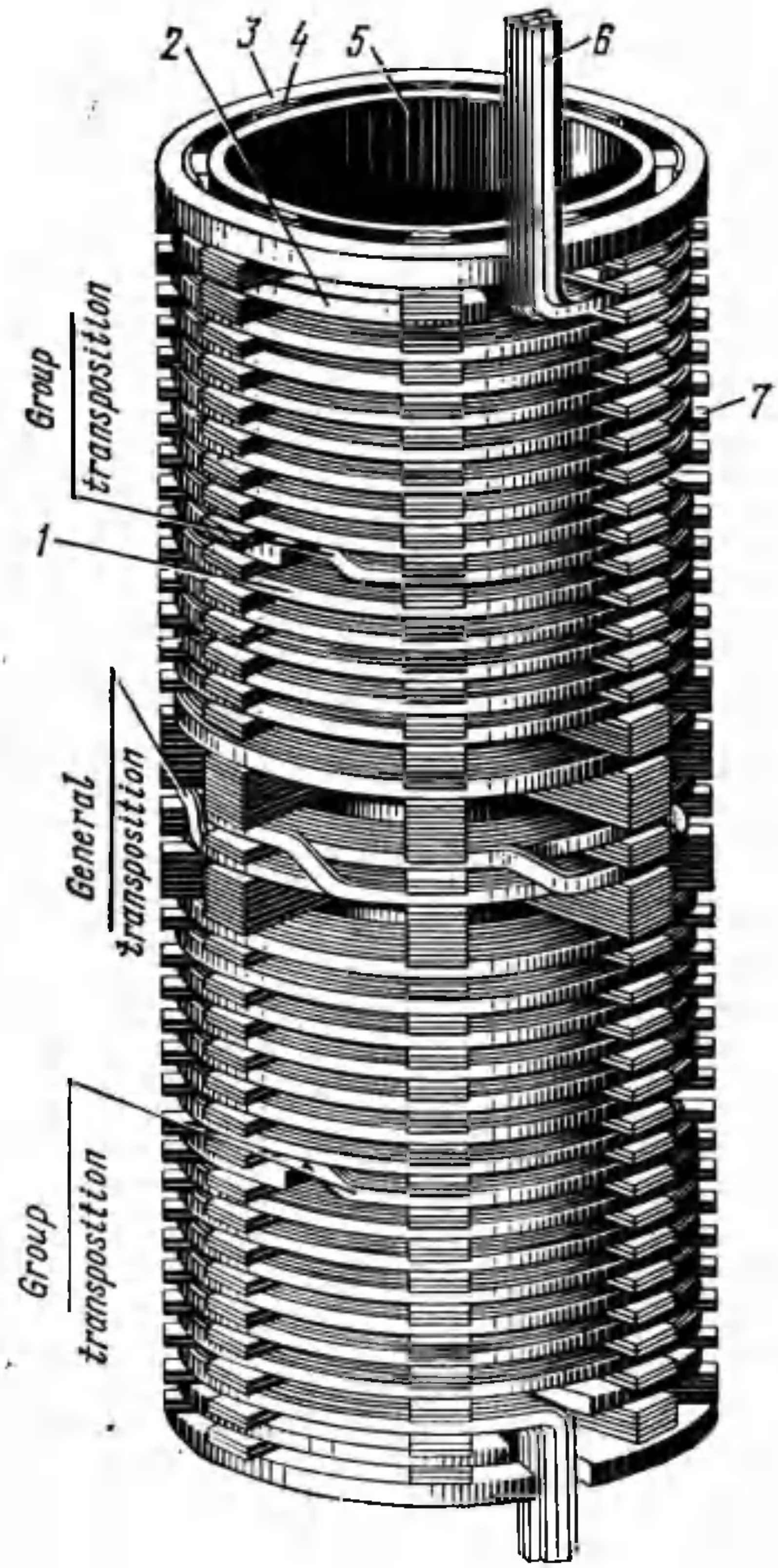


Fig. 3.23. Helical winding wound with eight parallel conductors

1—winding turn; *2*—segment; *3*—support ring; *4*—bar; *5*—paper-base laminate cylinder; *6*—parallel-conductors; *7*—insulating spacer

temporary steel cylinders (templates). The end faces of the winding are made level by gradually increasing the thickness of the spacers between the coil-end turns and insulation rings.

Since the parallel conductors in the helical winding are arranged concentrically and are at different distances from the winding axis, the conductors closer to the axis will be shorter than those farther away (as in the continuous-disk winding), unless some special measures are taken.

To equalize the resistances and inductive reactances of the parallel conductors and reduce the losses due to circulating currents caused by stray fluxes, the conductors are transposed three times each (see Fig. 3.24*a*). At one-fourth and

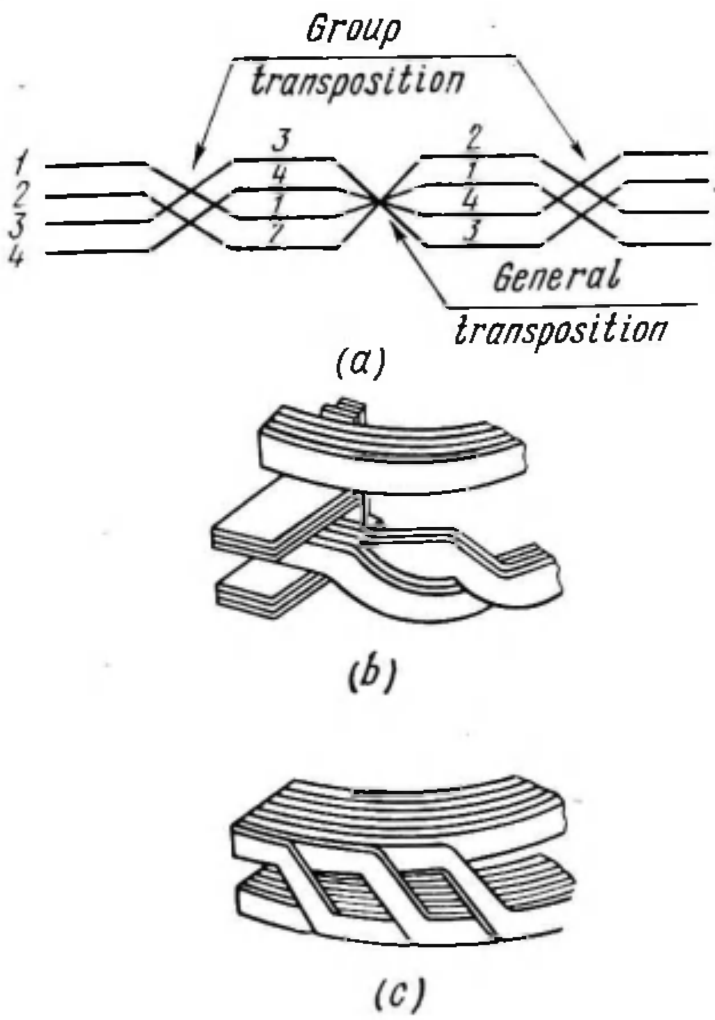


Fig. 3.24. Transposition of conductors in a helical winding

(*a*) transposition diagram; (*b*) group transposition; (*c*) general transposition

three-fourths of the winding's height, the conductors are divided into two equal groups, and the groups are transposed (Fig. 3.24*b*). These are group transpositions. In the middle of the winding, all the conductors are transposed (Fig. 3.24*c*). This is general transposition. The transpositions are made in the free spaces between the spacing blocks separating the turns.

As a result of the transpositions, the conductors of the helical winding (which usually have an even count) change places in consecutive order, so that each conductor takes each

possible position, and the lengths of all the conductors are thus equalized.

To make the transitions smooth and to equalize the radial sizes of the winding turns, special insulating wedges are placed under the conductors at places where the transpositions are made.

Besides the singly re-entrant helical winding considered above, doubly and quadruply re-entrant helical windings also find application. Multiply re-entrant windings are used where the number of parallel conductors per turn is rather great (from 18 to 50). The conductor transpositions in such windings are somewhat complex, but, on the other hand, they are more perfect, because the conductors during winding are made to continually pass from one winding re-entry into another. Such a transposition is called distributed, or Hobart's transposition. There are also other types of transposition, for example, uniformly distributed and DeBuda's transposition.

Helical windings have a comparatively small number of turns; they are wound for heavy currents and are mainly used in Size III through VII transformers.

3.5. Tapping Switches (Tap-Changers)

As already stated, the voltage of power transformers is controlled by changing the number of active turns in one winding with respect to another winding, i.e., by changing the transformation ratio. This is achieved by changing voltage-control taps provided on the respective winding.

Depending on their capacity, voltage class, and type of winding connection, power transformers use various tap-changing arrangements differing in type and construction.

Tap-changing arrangements intended for changing the taps of a single phase winding are called single-phase. If the taps in a three-phase transformer are changed by a single tap-changing arrangement, such an arrangement is referred to as three-phase.

The main units of an off-load (off-circuit) tap-changing arrangement are the *tapping switch* proper, comprising a system of fixed contacts to which the taps are connected and movable contacts which bridge the corresponding fixed con-

tacts, the *driving gear* or operating mechanism to operate the switch, and the *body* which carries all the tapping switch components.

According to their construction, off-load tap-changing arrangements have the following letter designations:

П and ПТ—respectively single- and three-phase drum-type tap-changers with slip-ring contacts;

ПС and ПТС—respectively single- and three-phase drum-type tap-changers with segment contacts;

ПЛ and ПТЛ—respectively single- and three-phase drum-type tap-changers with knife-blade contacts;

ПР and ПТР—respectively single- and three-phase rack-type tap-changers with knife-blade contacts.

The type designation of an off-load tap-changer indicates its construction (the letter designation), number of terminals per phase, rated voltage and current. If several tap-changers are ganged on a common shaft (rod), their number (preceded by the multiplication sign) is also indicated in the type designation. The type designations of the three-phase star-connected off-load tap-changers contain the numeral 0 following the letter designation. The year of approval of specifications for a given off-load tap-changer is given at the end of its type designation.

As an example, the type designation П6-35/160 × 3-73 reads: single-phase drum-type off-load tap-changing arrangement with slip-ring contacts and six terminals per phase, rated at 35 kV and 160 A, comprising three tap-changers ganged on a common shaft, and approved in 1973.

The on-load tap-changing arrangements which are used on power transformers manufactured in this and other countries differ in design, but all of them can be classified into slow-action tap-changers using inductive current-limiting (divertor) impedances (reactors) and quick-action tap-changers employing resistive current-limiting impedances (resistors).

According to their construction, on-load tap-changing arrangements have the following letter designations:

PHO and PHT—respectively single- and three-phase tap-changers using no current-limiting impedance;

PHOP and PHTP—respectively single- and three-phase tap-changers with an inductive current-limiting impedance;

PHOA and PHTA—respectively single- and three-phase tap-changers with a resistive current-limiting impedance.

The type designation of an on-load tap-changer indicates its construction (the letter designation), rated voltage and current, and the type of the divertor switches used. The divertor switch type is indicated by an additional letter (A for air-break switches, Г for gas-break switches, B for vacuum-break switches, and П for switches equipped with semiconductor arc suppressors; oil-break switches have no special letter designation). The type designations of the three-phase star-connected on-load tap-changers contain the numeral 0 following the letter designation. If several tap-changers are operated by a common driving gear, their number (preceded by the multiplication sign) is also indicated in the type designation. The year of approval of specifications for a given tap-changer is given at the end of its type designation.

For example, the type designation PHTA-0-35/1000-73 should be read as follows: three-phase star-connected on-load tap-changer using current-limiting resistors, rated at 35 kV and 1 000 A, equipped with oil-break divertor switches, and approved in 1973.

Let us consider the design and operation of some off- and on-load tap-changers in more detail.

Three-Phase Off-Load Tap-Changers for Windings with Taps Arranged Near the Neutral End

The ПТР-0-10/63 × 3-65 and ПТР-0-35/63 × 3-65 rack-type five-step tap-changers are intended for changing taps within $\pm 2 \times 2.5\%$, with the taps arranged near the neutral end of the windings in accordance with the diagrams of Fig. 1.25*a* and *c*, or the like, in Size I through III transformers. They are similar in design, the only difference being in creepage distances.

Referring to Fig. 3.25, a thick-walled paper-base laminate tube *1* carries three groups of fixed brass contacts *2* (five contacts per group) arranged in a single row. One end of a fixed contact (terminal stud) has a smooth cylindrical surface which engages a movable contact *3*, while its other end is threaded and is fitted with a set of nuts and washers to

connect the winding taps in accordance with the designations given in the diagrams of Figs. 1.25*a* and *c*, and 3.17.

The movable contacts (one per group of fixed contacts or phase) are made from sheet brass and have the shape of tongs. One end of each movable contact is rigidly held by a bolt *5* to a rack *6*, and its other end, the one that is made in the form of jaws, embraces from two sides the cylindrical

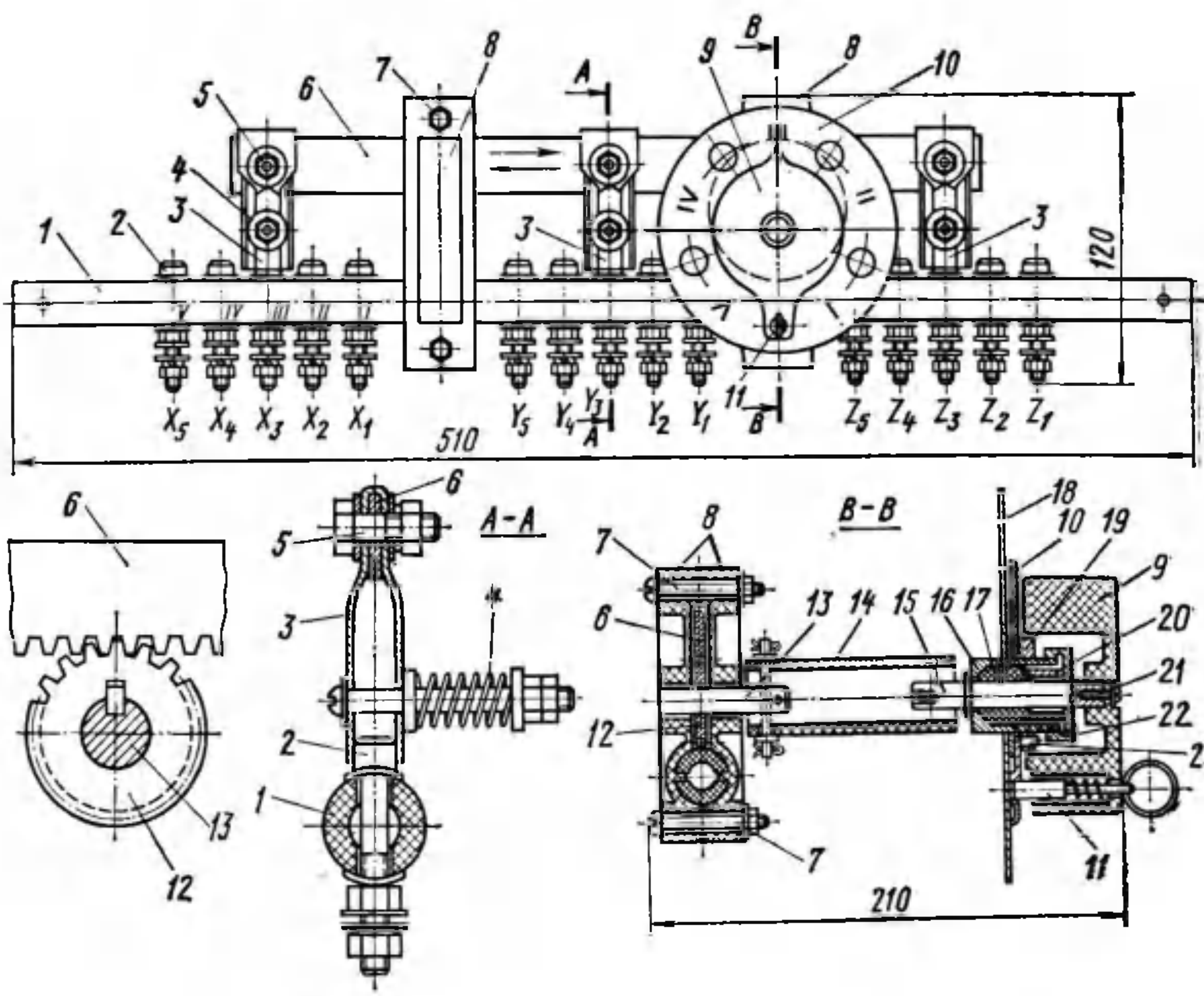


Fig. 3.25. Type ПТР-0-10/63 × 3-65 three-phase off-load tap-changer

portion of a fixed contact, thus forming a sliding connection. The movable contacts are tightly pressed against the fixed contacts by coil springs *4*.

The rack is a current-carrying strip which, together with the three movable contacts, forms a rigid bridge connecting the windings in a star by bridging the corresponding taps. The taps are changed by shifting the movable contact system to the right or left relative to the fixed contacts.

The movable and fixed contacts are joined to form a single system by means of two holders *8* made of a glass-fabric-base laminated material. Each holder consists of two symmetrical halves (cheeks) which hold from two sides the tube *1* and rack *6*. The tube is rigidly fixed in the holders, while the rack is free to move longitudinally between the holder halves.

Tap changing is effected by means of an operating mechanism (driving gear) comprising a pinion *12* which engages the rack. The pinion is keyed to a shaft *13* installed in one of the holders. The shank of the shaft is coupled by cottered pins to a paper-base laminate tube *14* which is in turn coupled to the shaft *15* of an operating knob *9*. The knob is splined to its shaft and is fixed in place by a screw *21*. The tube *14* doubles as a drive member transmitting rotary motion and as insulation between the rack and the tank cover of the transformer.

To prevent leakage of transformer oil from the tank along the shaft *15*, use is made of a packing gland comprising a packing *17*, bushes *16* and *20*, and a gland nut *22*.

A tin-plate dial *10* bears Roman numerals indicating the voltage steps and is provided with five holes to lock the switch in each operating position by means of a spring stop *11*. The dial is also provided with two rigid stops at the extreme positions I and V, which serve to limit the rotation of the operating knob. The dial is fastened to the tank cover *18* by a nut *19* and a set screw *23*.

Inside the transformer, the tap-changers are fastened to two brackets on the top yoke clamps by means of bolts passing through holes in the tube *1*.

Type ПТС-0-9-120/10 Tap-Changer (Fig. 3.26*a*) is used in transformers with a capacity from 100 to 1 000 kV A for voltages up to 10 kV, that were manufactured until 1967. The contact system of this switch (rated at 120 A) comprises nine fixed contacts *1* and two self-adjusting segment-type movable contacts *4*. Bridging the respective phase-winding taps connected to the fixed contacts, the segments (contact shoes) form a neutral point and thus connect the windings in a star.

The switch provides for three voltage-control steps: bridging the contacts X_1, Y_1 and Z_1 (see Fig. 3.26*b*) gives Step *I*

(+5%), contacts X_2, Y_2 and Z_2, Step *II* (rated), and contacts X_3, Y_3 and Z_3, Step *III* (—5%).

A paper-base laminate cylinder *2* (Fig. 3.26*a*) serves as a support for the fixed contacts. The contacts have a special shape and are bolted to the cylinder. Their cylindrical sur-

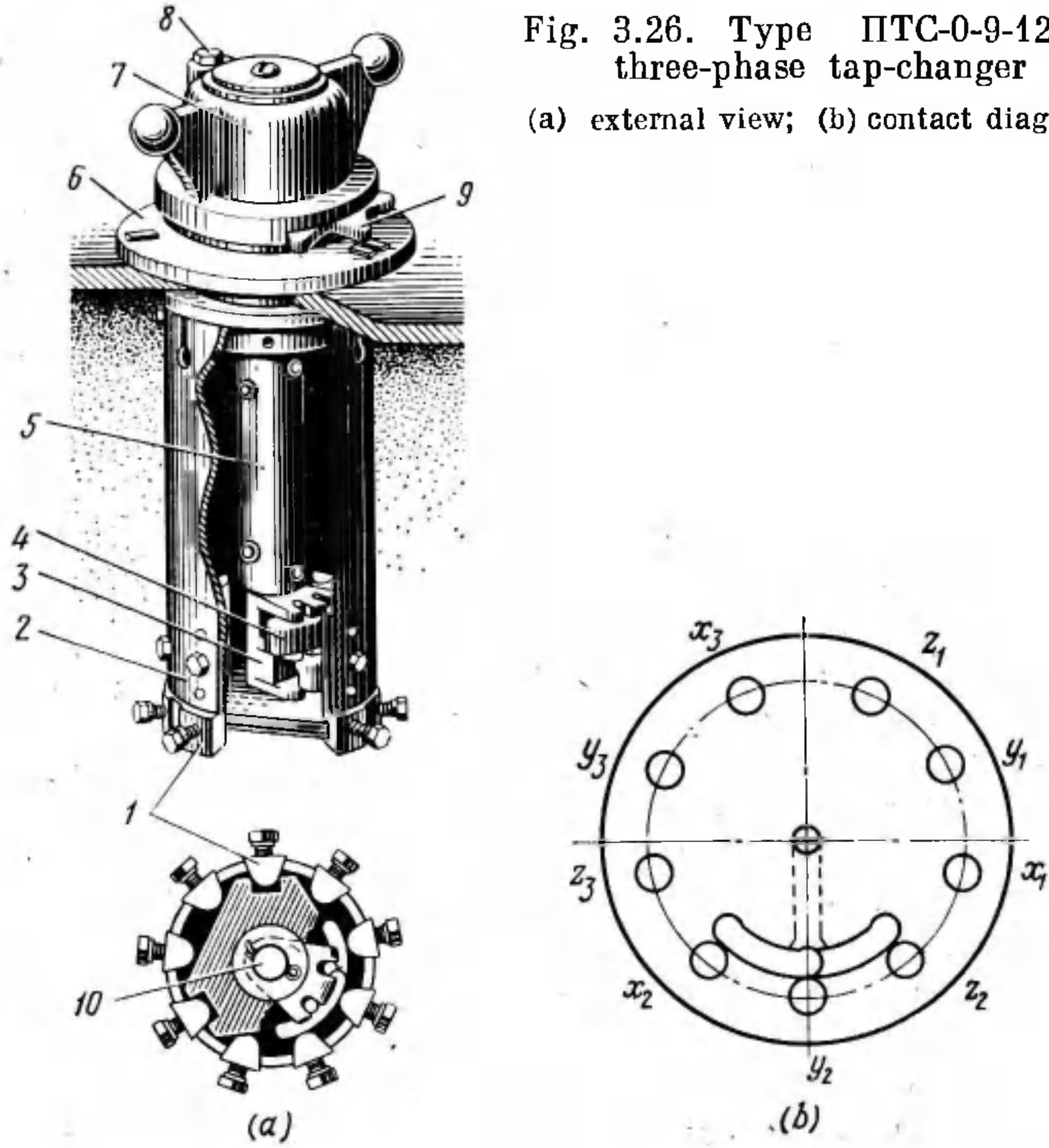


Fig. 3.26. Type ПТС-0-9-120/10 three-phase tap-changer

(a) external view; (b) contact diagram

faces face the contact shoes, while the shanks pass outside through the cylinder wall and serve for bolting the taps.

The contact-shoe segments are held to a crank *3* and, thanks to the special arrangement of their pivots and pressure springs, are capable of adjusting themselves to fit the fixed contacts most tightly.

A crankshaft *10*, a paper-base laminate tube *5* and the shaft of an operating knob *7* are joined together to form the operating shaft of the switch. The operating-knob shaft passes through the switch flange *6* which is provided with a pack-

ing gland to prevent leakage of transformer oil along the shaft. The lower end of the crankshaft is centred in a paper-base laminate plate. To change the taps, one should undo a stop bolt *8* and turn the operating knob until an index *9* is set against the numeral indicating the desired voltage step on the switch flange.

Type ПТЛ Tap-Changers are fitted with knife-blade contacts. Such contacts perform better and are more reliable than the segment type. A knife-blade contact (Fig. 3.27) usually consists of two slightly curved copper strips (jaws) *1* which are tightly pressed by springs *2* against a contact blade *3*.

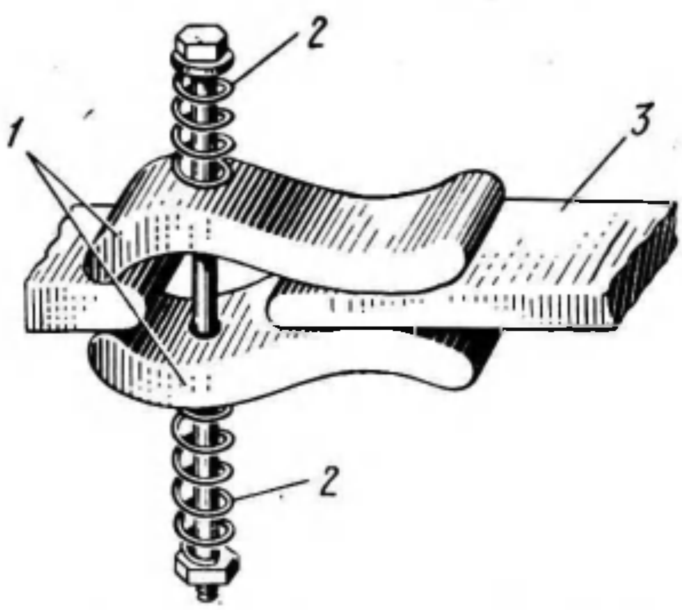


Fig. 3.27. Knife-blade contact

The ПТЛ-9-120/10 and ПТЛ-9-120/35 tap changers (the former for voltages up to 10 kV and the latter, up to 35 kV) are used in Size II and III transformers wound for a three-step voltage control with taps arranged near the neutral end (including those wound in accordance with the reverse tapped-winding arrangement). The contact systems of both tap-changers are rated at 120 A. The switches are similar in design, the only difference being in the creepage distances.

Figure 3.28 shows the construction of the ПТЛ-9-120/35 tap-changer. The metal flange *1* of the switch serves for installing the switch on the transformer tank cover, the flange-to-cover joint being sealed with a rubber gasket. A steel shaft *6* with an operating knob *2* splined to its top end passes through the flange and is sealed in it by means of a packing *8* and a gland nut *3*. The correct position of the knob on the splines of the shaft is secured by a set pin *4*, and the knob is fixed in place by means of an endplate and a screw *5*. A set bolt *7* locks the switch in each operating position indicated by numerals *I*, *II* and *III* on the switch flange (there is an index on the knob, that is set against these numerals when changing taps). The lower end of the operating knob shaft is

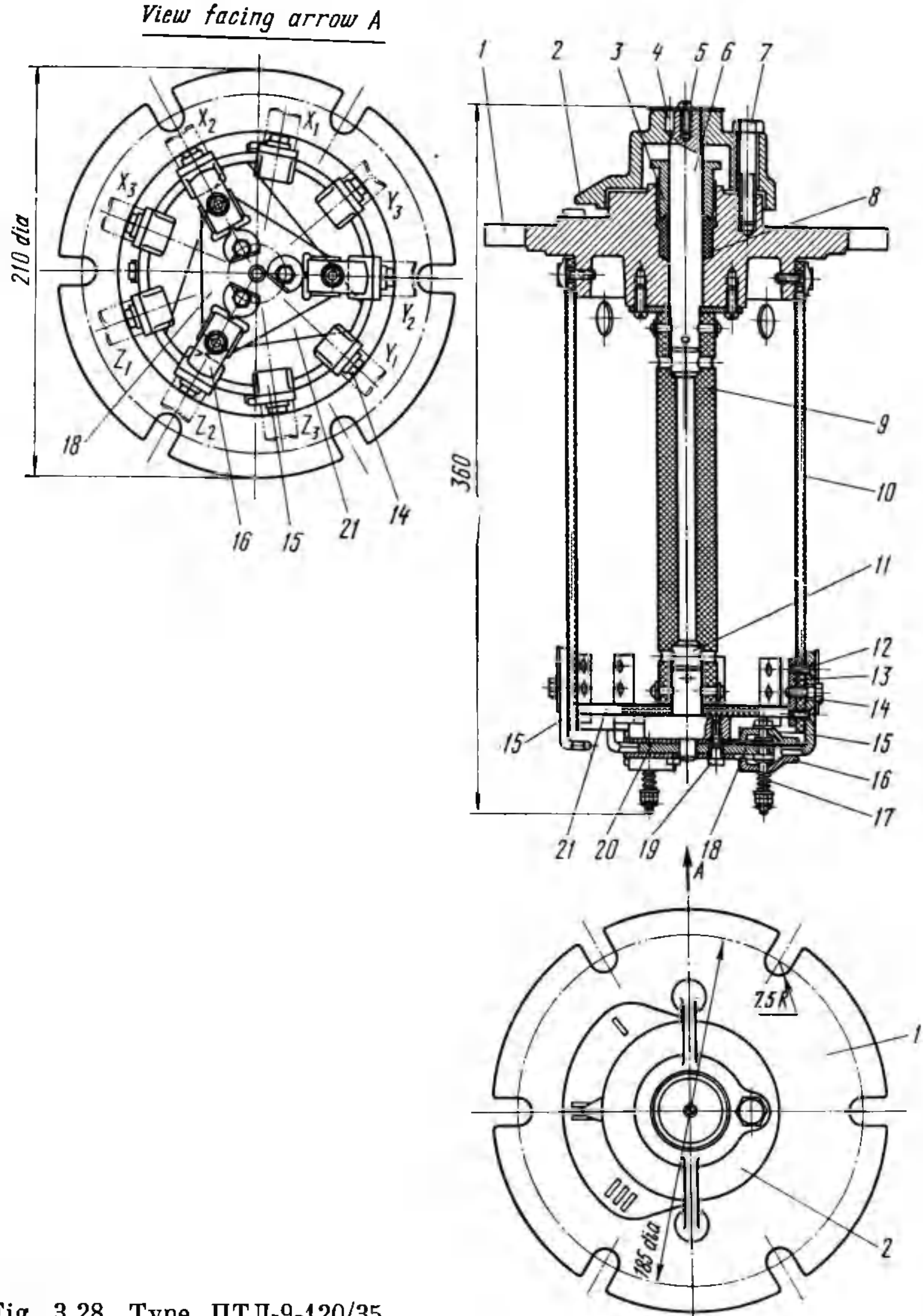


Fig 3.28. Type ПТЛ-9-120/35 three-phase off-load tap-changer

coupled to a thick-walled paper-base laminate tube *9* which insulates the movable contacts from the switch flange while transmitting rotary motion from the knob shaft to a contact shaft *11* whose lower end carries a triangular contact plate *18* and dogs *20*. The plate and dogs are rigidly held to the contact shaft by bolts *19*.

Three pairs of movable contact jaws *16*, pressed together by springs *17*, are mounted at the corners of the contact plate *18* on special pivots provided with nuts and washers. The plate with the contacts as a whole forms the neutral point of a star connection. The fixed contact system comprises nine contact blades *15* which are placed equidistantly along the circumference of a paper-base laminate cylinder *10* and held to it by screws *12* and plates *13* provided with threaded holes.

The cylinder *10* is rigidly fastened to the switch flange *1*. It doubles as a support and insulation for the fixed contacts. A paper-base laminate plate *21* centres the operating shaft and forms the base of the switch. The winding taps are connected to the fixed contacts by means of bolts *14* in accordance with the designations given in the diagram of Fig. 3.28.

The operation of the switch is clear from the figure: when the operating knob is turned through an angle corresponding to a voltage-control step (in our case, through 40°) the movable contacts connect the like taps of the phase windings in a star at the desired step. To change the taps, one should de-energize the transformer, undo the set bolt *7* and remove it from the operating knob, set the switch to the desired position by turning the knob until its index is against the numeral indicating the given voltage step, screw home the set bolt, and energize the transformer.

Similar tap-changers are also available for a five-step voltage control within the range $\pm 2 \times 2.5\%$.

Three-Phase Off-Load Tap-Changers for Transformers Wound in Accordance with the Direct Tapped-Winding Arrangement

The tap-changers for such winding arrangements (see Fig. 1.25*b*) are put out for voltages from 10 to 35 kV at 120, 200, and 400 A. There are three- and five-step switches for windings with four and six tappings, respectively. The

switches are equipped with knife-blade contact systems. In accordance with the number of taps, rated current, and voltage class, the tap-changers are designated ПТЛ-4-120/35, ПТЛ-6-200/10, ПТЛ-6-200/35, etc. Older tap-changers of this class were provided with segment-type contact systems and, accordingly, were designated ПСС-4-120/35 and so on (the second letter C in the type designation means that the given tap-changer consists of three gang-operated single-phase switches).

Type ПТЛ-6-200/10 Tap-Changer (Fig. 3.29) is a gang-operated three-phase switch. It comprises a paper-base laminate cylinder *4* carrying fixed contacts *7* (of which there are six per phase) arranged in three tiers, one above another. The contacts are of knife-blade construction and project inside the cylinder. An insulating shaft—paper-base laminate tube *5*—carrying movable contact jaws *6* runs the whole length of the cylinder. The movable contacts bridge a pair of fixed contacts in each phase (tier) simultaneously. Their construction is clear from the figure. The voltage taps are terminated at the fixed contacts on the outside of the cylinder.

The top end of the paper-base laminate tube is coupled to the main steel shaft *1*, the bottom end of the tube being coupled to an auxiliary steel shaft *8*, and the composite switch shaft thus obtained is centred in bearing bushes *3* installed in metal flanges *2* which are fastened to the cylinder *4* at both its ends. At the bottom end of the cylinder there is also a disk *13* which is held to the bottom flange by long bolts *9*.

The shank of the auxiliary shaft carries a lock *10* which is rigidly fixed to it by pin *12*. The lock is made in the form of a three-pointed star with spring stops *11* at its points. The stops fit into holes in the disk, thus locking the switch in each operating position.

Inside the transformer, the tap-changer is installed on brackets held to the core-coil assembly, for which purpose use is made of three holes provided in the top flange and bolts *9* in the bottom flange.

Type ПТЛ-6-400/10 and ПТЛ-6-400/35 Off-Load Tap-Changers differ from the tapping switch described above in the size of the insulating cylinder and the length of the pa-

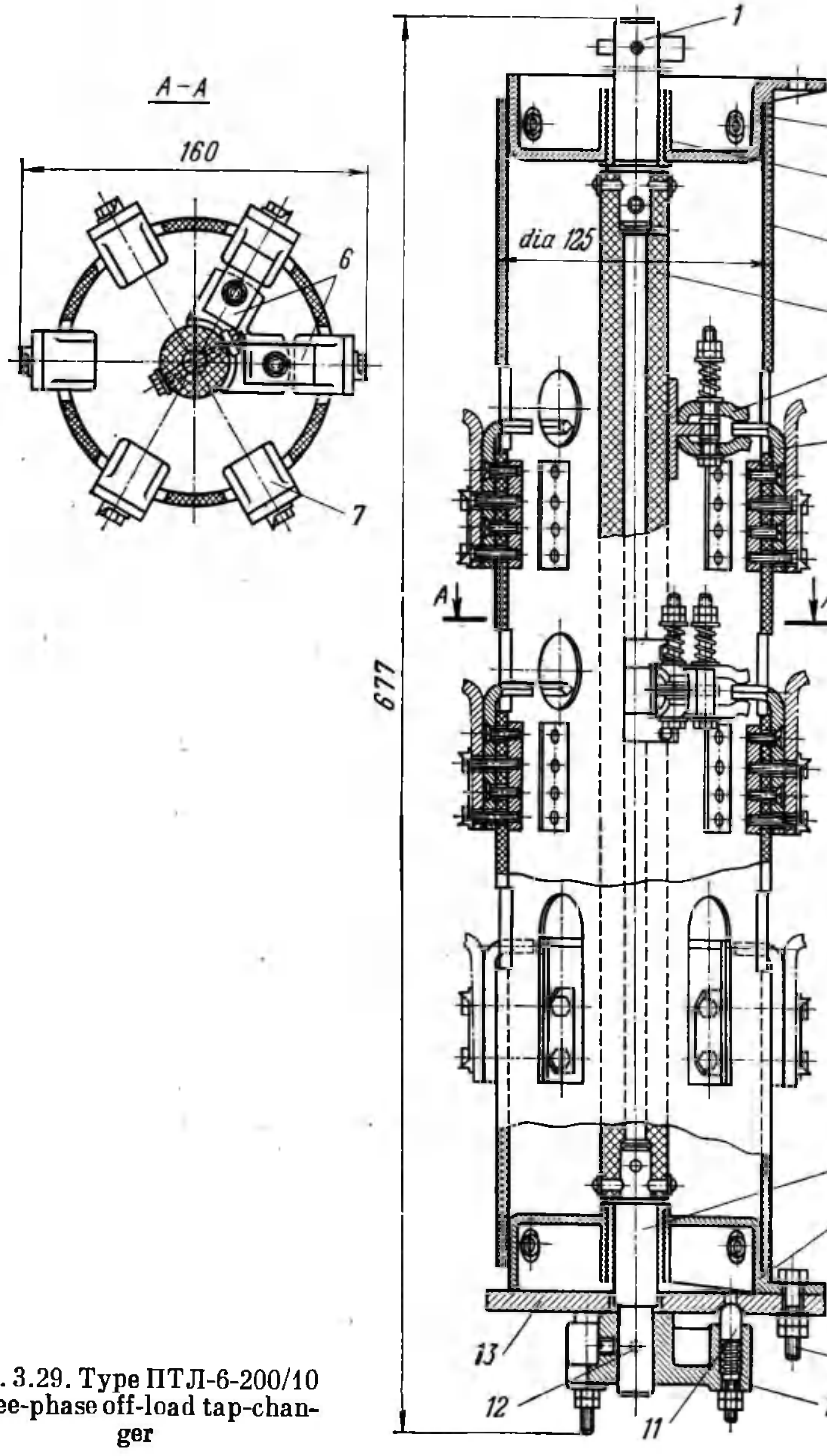


Fig. 3.29. Type ПТЛ-6-200/10 three-phase off-load tap-changer

per-base laminate tube. Besides, their contact systems are reinforced by pairing the contacts.

The operating mechanism for the above tap-changers is mounted on the tank cover of the transformer. Its construction is considered in detail elsewhere in the text.

Single-Phase Off-Load Tap-Changers

Transformers of Size IV and bigger, with off-load tap changing, use for the purpose single-phase five-step drum-type tap-changers. In this case, the transformer must be

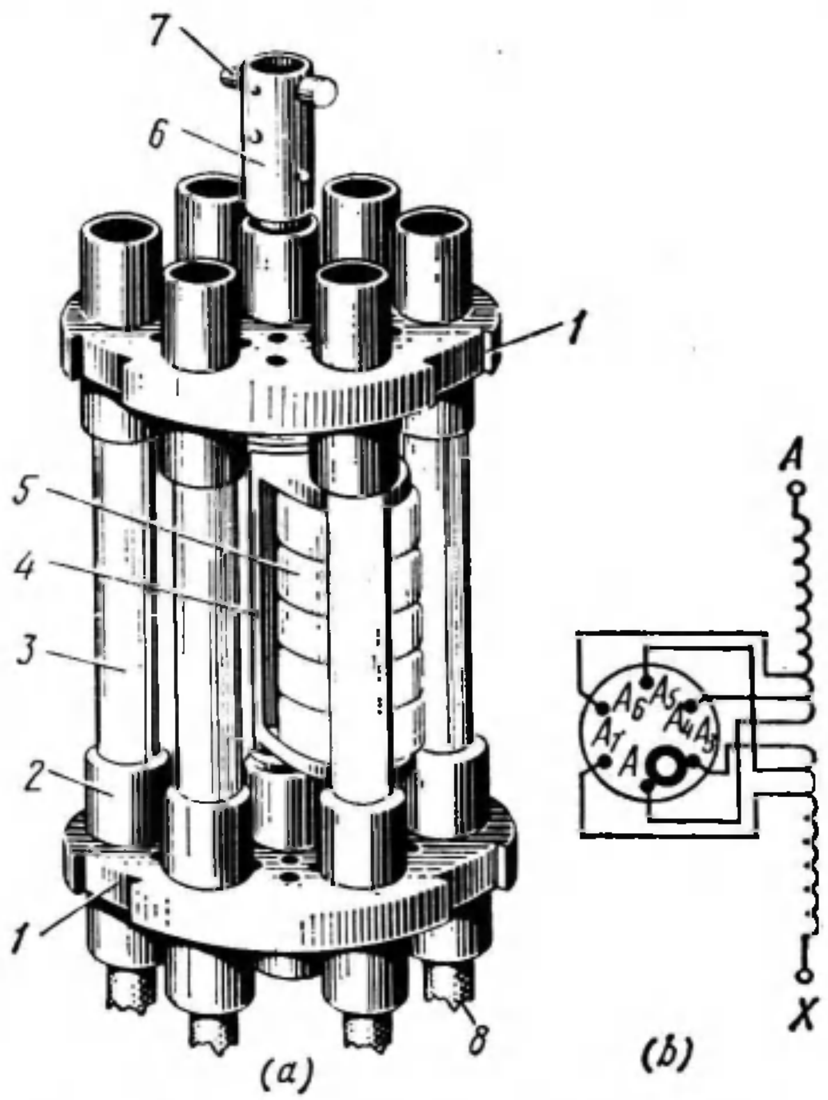


Fig. 3.30. Type П6 off-load tap-changer

(a) external view; (b) tap-changing diagram

wound in accordance with the direct six-tap winding arrangement (see Fig. 1.25*b*). These switches are available in voltages from 10 to 220 kV and currents from 16 to 1 600 A.

Type П6 Tap-Changer (Fig. 3.30*a*) consists of two (top and bottom) paper-base laminate disks *1*, paper-base lami-

nate sleeves *2* press-fitted into the disks, nickel-plated brass rods *3* serving as fixed contacts, and nickel-plated brass rings *5* which are spring-mounted on a crankshaft *4* and operate as movable contacts.

The top end of the crankshaft passes through the central sleeve of the top disk and carries at its end a steel coupling sleeve *6* with a pin *7* intended for coupling the crankshaft to the operating rod of the driving gear to make possible tap changing by shifting the rings *5* from one position between the rods *3* to another.

Leads *8* connecting the rods to the winding taps are fitted with special terminals which are soldered into the rods (in some designs, the terminals are screwed into the rods). Where heavy currents are to be handled, the taps are connected to both ends of the corresponding rods.

Depending on the switch position, the movable contact rings bridge the rods and hence, the respective winding taps. Fig. 3.30*b* shows a tap-changing diagram for a six-tap winding arrangement (one phase is only shown).

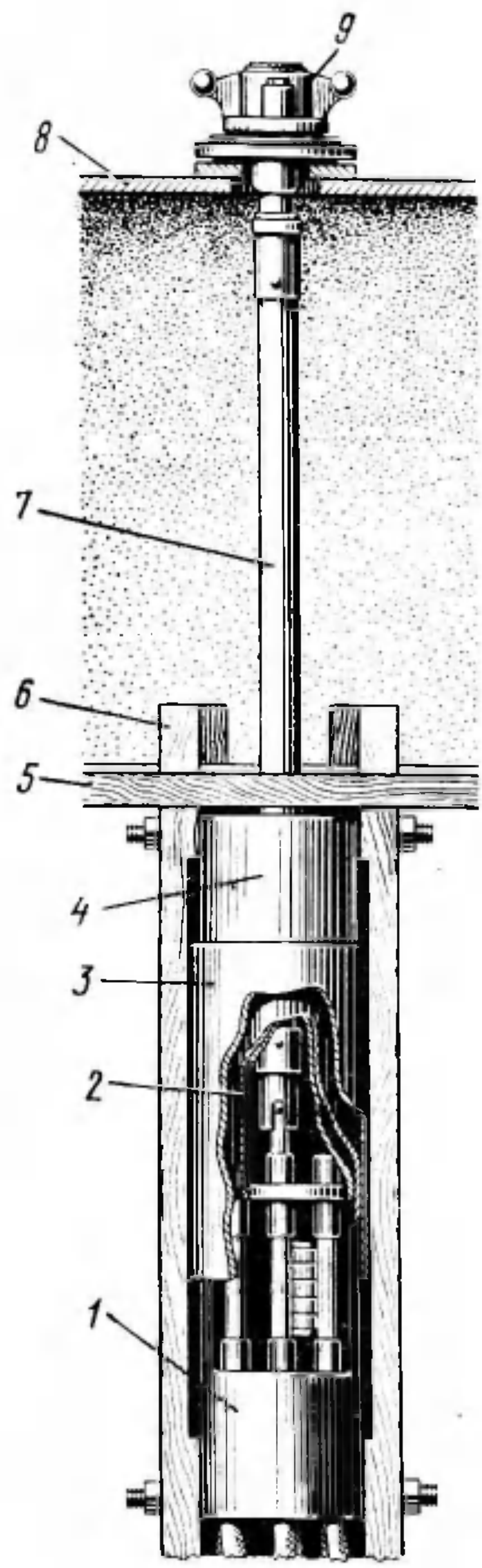


Fig. 3.31. Installation of the Type П6 off-load tap-changer in a transformer

The installation of the Type П6 tap-changer in a transformer is illustrated in Fig. 3.31. The switch is held to the yoke clamps by means of a set of mounting paper-base laminate cylinders (*1*, *2*, *3* and *4*) and wooden supporting strips (*5* and *6*). The switch disks are provided each with three recesses (mortises) on the periphery, into which fit the correspondent projections (tenons) of two short cylinders *2*, one cylinder being installed above the top disk and the other, below the bottom disk.

The switch together with the short cylinders is inserted into a common long cylinder *4*. At the top and bottom, the short cylinders are fixed to the long one by means of fabric-base laminate studs which also secure the cylinders to the vertical wooden strips.

The contact system of the switch can be inspected through a window cut in the long cylinder wall facing the tank wall. The window is closed by the sliding cylinder *3* which rests on the shoulders of the vertical supporting strips and can be easily lifted when inspecting the contacts.

The switch is installed on the core-coil assembly of the transformer so that the contact rods A_2, B_2, and C_2 are opposite the nearest tank wall, and is actuated by an insulating operating rod *7* whose one end is coupled to the shaft of an operating knob *9* mounted on top of the tank cover *8* and the other end, to the crankshaft of the switch.

The Operating Mechanism

The off-load tap-changers are usually hand operated. The chief components of their operating mechanism are the operating rod and knob. Referring to Fig. 3.32*a*, the lower end of a paper-base laminate rod *6* carries a coupling sleeve *7* whose forked end freely engages pin *8* of a coupling sleeve *9* which is tightly fitted onto the end of the switch crankshaft *10*.

The top end of the operating rod is articulated to the operating knob shaft: a fork pin *4* is loosely fitted into a hole in a forked coupling sleeve *2* made fast to the knob shaft, and the steel coupling sleeve *5* of the operating rod is coupled to the fork pin by means of another pin *3* fitted with a spring clip which prevents the pins from working out. Such an articulation enables the coupling sleeves to pivot on the pins with respect to each other, thus compensating for their possible misalignment when assembling the operating mechanism.

The position of the operating knob *13* (Fig. 3.32*b*) relative to the contact system of the switch is adjusted by means of an indexing ring *14*. The ring is keyed to a shaft *18* and is fastened to the knob by a screw *11* passing through one of the nine holes provided in the ring. In the knob bore, there

are ten threaded holes to fit the screw *11*. The holes in the ring and knob bore are spaced at regular intervals along a circumference of the same diameter. The central angle between the axes of the adjacent holes in the ring is 40° (360°/9)

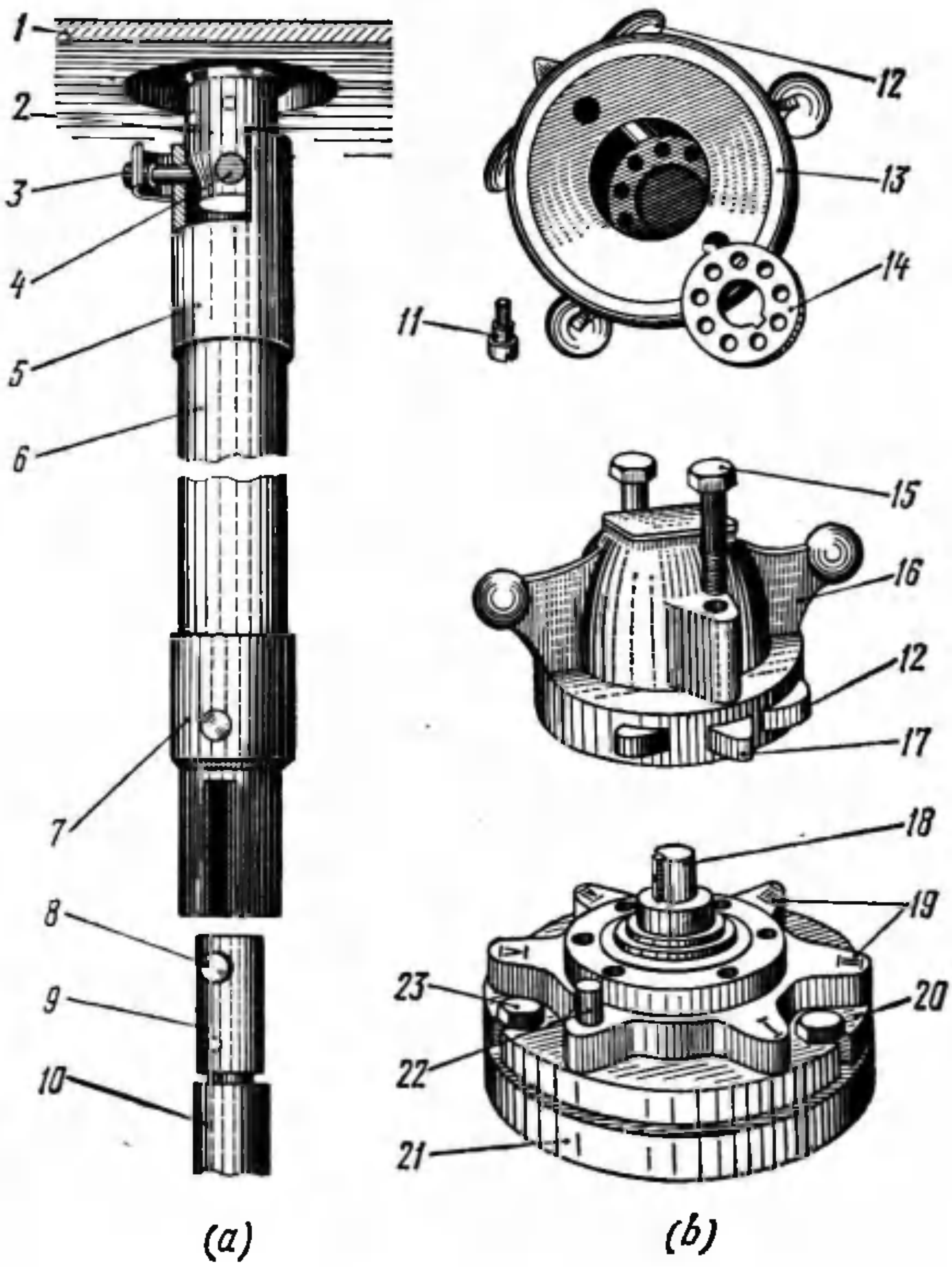


Fig. 3.32. Operating mechanism of the Type П6 tap-changer

(*a*) coupling of the operating rod to the operating knob shaft and the crankshaft of the switch; (*b*) components of the operating knob

and that in the knob bore, 36° (360°/10). This makes it possible to fix the ring in the knob in positions differing from one another by an angle of 4° (40-36°), or by an angle which is a multiple of 4°, i.e., 8°, 12°, 16°, etc.

The switch mounting pad *21* is welded to the tank cover *1* (Fig. 3.32*a*), and a switch flange *20* provided with a pack-

ing gland is fixed to the pad by three bolts *23*, a rubber gasket being placed between the pad and the flange. The operating knob shaft *18* passes through the switch flange and is sealed in it by the packing.

The switch flange has six projections *19*. Five of them bear the numerals (*I*, *II*, *III*, *IV*, and *V*) indicating the voltage steps, while the sixth carries a stop *22* which limits the rotation of the operating knob. On the centre lines passing through the projections, in the switch flange there are six tapped holes to fit the two set bolts *15* of the operating knob.

The crankshaft of the switch is shifted from position to position by turning the operating knob handle *16* through 60°. In each position, the knob index *17* must be in alignment with the centre line passing through the respective projection of the switch flange, and the two holes for the set bolts in the knob must coincide with two of the six holes in the flange. Projections *12* on the knob and the stop *22* prevent the switch from being shifted from position *I* to position *V*, and vice versa, without passing through the intermediate positions.

When repairing and assembling the operating mechanisms, it may happen that the position of the operating knob does not correspond to that of the movable contact rings, i.e., with the set bolts *15* screwed home, the knob index is displaced relative to the centre line passing through the flange projection that bears the numeral indicating the given voltage step. In this case, one has to adjust the position of the operating knob on its shaft by using the indexing ring. To this end, one should remove the set bolts and turn the knob in either direction until a good contact between the contact rings and the corresponding contact rods is attained, noticing in so doing the direction and approximate amount of angular displacement of the knob index from the centre line of the flange projection bearing the corresponding numeral. Then, one should remove the knob from its shaft, undo the screw that holds the indexing ring to the knob, turn the ring in the knob bore so as to ensure that the keyway in the ring is displaced through the angle required to compensate for the noticed angular displacement of the knob index, drive the screw home through the ring hole which in this posit-

ion of the ring coincides exactly with one of the holes in the knob bore, and install the knob on the shaft.

Now, if the knob index is set against the numeral indicating the given voltage step and the holes for the set bolts in the knob coincide precisely with two of the holes in the switch flange, the adjustment is finished. If the set bolt holes in the knob and flange do not coincide exactly, the adjustment should be repeated.

On-Load Tap-Changers

An on-load tap-changer consists essentially of the following components: a *selector switch* intended, as its name implies, for selecting the required winding tap without interrupting the load current; a *reversing switch* which serves for extending twofold the voltage-control range by reversing the connection of the regulating winding relative to the excitation winding; a *divertor switch(es)* designed for transferring the power circuit (load) from tap to tap; *current-limiting* (divertor) *impedance* (preventive autotransformer or bridging reactor in slow-action tap-changers, or resistor in quick-action tap-changers) used for the purpose of shunting the load current from one winding tap to the next without interfering with the load and designed to limit the resulting circulating current to a safe value during the interval that two adjacent taps are bridged; and an *operating mechanism* which can be actuated either manually (with a handle) or by means of a motor driving gear controlled manually (by push buttons) or automatically. In addition, such a tap-changer includes various ancillary apparatus, signalling devices, automatic control equipment, etc.

On-Load Tap-Changers Using Current-Limiting Reactors. Types PHT-13-625/35 and PHT-13-625/110 nine-step switches serve to change taps arranged at the neutral end of the windings in transformers for 35 and 110 kV, respectively. In these tap-changers, the selector switch is installed along the core-coil assembly under the transformer tank cover. If the selector switch is installed across the core-coil assembly, the type designation of a given tap-changer contains the letter A following the numeral indicating the modification number, e.g., PHT-13A.

Type PHT-18-1200/35 23-step tap-changer includes a reversing switch and is mainly used in booster step-voltage regulators. It consists of three gang-operated single-phase on-load tap-changers mounted on a common frame.

Type PHT-20-625/35 tap-changer has the same ratings as Type PHT-13-625/35, but its breaking capacity is much higher. It is equipped with divertor switches of the circuit breaker type with knife-blade main contacts and bridged arcing contacts.

Some on-load tap-changers, e.g., Types PHT-9-150/10 and PHT-9-150/35 (nine-step switches rated for 150 A at 10 and 35 kV, respectively), have no current-limiting reactors. They are fitted with selector switches of the contactor type that permit of the taps being changed with rupturing the power circuit. Such tap-changers are used in transformers with a capacity up to 6 300 kV A, where the breaking capacity need not be very high.

Three-phase on-load tap-changers comprise three gang-operated single-phase tapping switches mounted on a common base (plate, frame).

The operation of a single-phase on-load tap-changer using a current-limiting reactor is illustrated in Fig. 3.33. As is seen from the diagram, the circuit comprises two symmetrical branches. Let us analyze the sequence of operation of the contact systems of the component switches while changing from tap X_m to tap X_n.

In the normal operating position on tap X_m (Fig. 3.33*a*), both divertor switches (*DS1* and *DS2*) are closed, and both selector switch contacts (*SC1* and *SC2*) are closed on tap X_m. The load current I_l divides equally between the two halves of the centre-tapped reactor winding. Since the currents in the two halves of the reactor are equal and flow in opposite directions, the resultant magnetic flux in the reactor core is zero. The inductive reactance of the reactor under this condition is therefore sensibly nil, hence there is practically no voltage drop through the reactor.

To move from tap X_m to X_n, use is made of an operating mechanism *4* which can be actuated either manually (with a handle) or by means of a motor driving gear with a push-button or automatic control. The tap-changing cycle proceeds in the following sequence. First, the divertor switch *DS2*

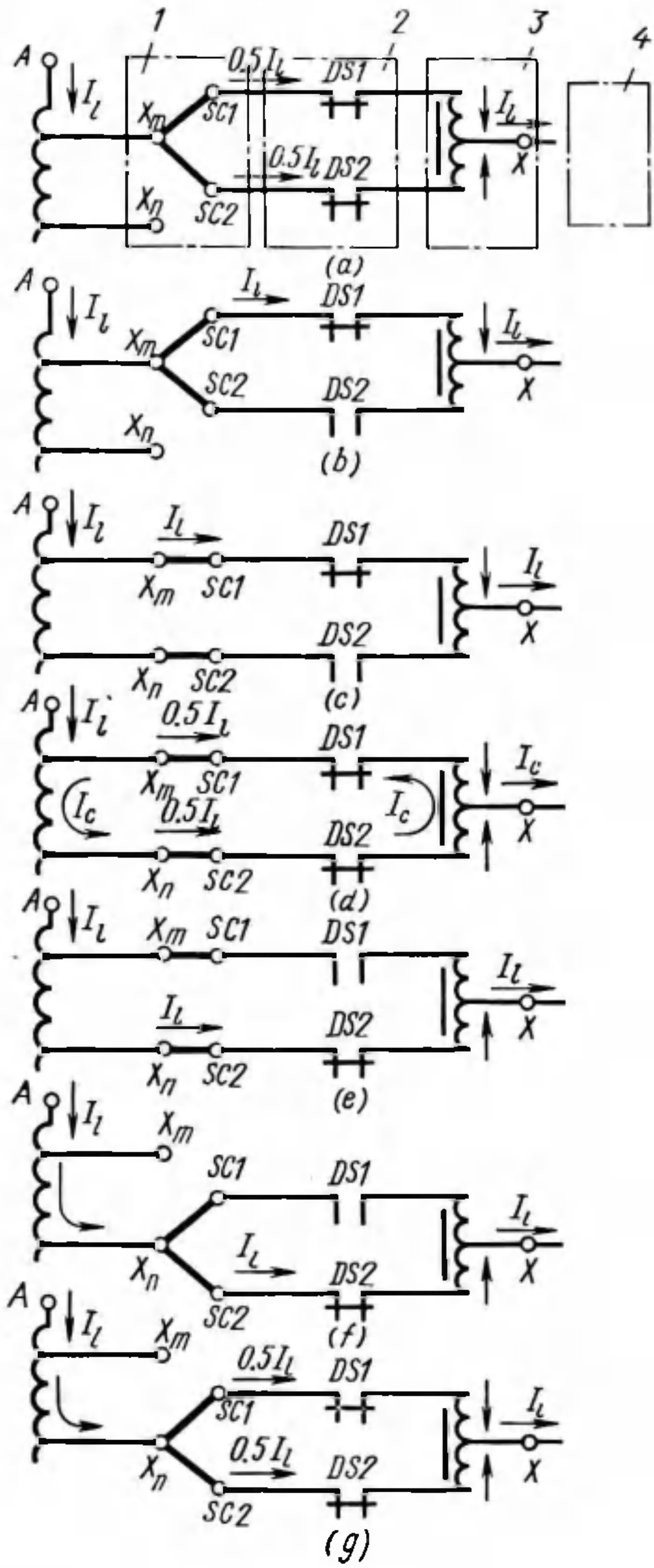


Fig. 3.33. Elementary diagram of an on-load tap-changer using a current-limiting reactor

(*a*) through (*g*) complete tap-changing cycle; *1*—selector switch; *2*—divertor switch(es); *3*—reactor; *4*—drive

opens (Fig. 3.33*b*), thus breaking the associated branch, and then, after a short time interval, the selector switch contact *SC2* closes on tap X_n (Fig. 3.33*c*).

Upon the opening of the divertor switch *DS2*, all the load current flows through one-half of the reactor winding (Fig. 3.33*b* and *c*) whose reactance causes some voltage drop through the reactor. Then the divertor switch *DS2* closes (Fig. 3.33*d*). In this position, called the bridging position, the load current again divides equally through the reactor winding halves, but at the same time, the voltage across the tap winding $X_m X_n$ is impressed on the reactor and causes a circulating current I_c to flow through an impedance loop formed by the tap winding and reactor. The magnitude of this current is directly proportional to the tap winding voltage and inversely proportional to the impedance in the loop. While flowing through the reactor winding, the circulating current magnetizes the reactor and thereby introduces an inductive reactance into the loop, which limits the current. It is precisely to limit the circulating current that the reactor is used in this circuit. If there were no reactor, the tap winding $X_m X_n$ would be short-circuited in the bridging position and would burn out because of the short-circuit current flowing through it. Thereafter, the divertor switch *DS1* opens (Fig. 3.33*e*) and, after a short time interval, the selector switch contact *SC1* closes on tap X_n (Fig. 3.33*f*) with the result that the load current now flows through the other half of the reactor winding. Closing the divertor switch *DS1* (Fig. 3.33*g*) completes the tap-changing cycle.

When changing to subsequent taps, the opening and closing of the switches is repeated in the above sequence.

As has been already stated, in the bridging position (Fig. 3.33*d*) the current flowing through one of the circuit branches is the sum of the 50-percent load current and the circulating current. This fact is taken account of when designing the current-limiting reactors to have a continuous rating, which permits of the bridging positions being employed as additional steps where an increased number of voltage-control steps is required. From the diagram of Fig. 3.33*d* it is clear that when the bridging position is used as an operating one, $2n - 1$ voltage steps are obtained with n taps.

Arrangement of On-Load Tap-Changer Components in a Transformer. Figure 3.34 shows the arrangement in a transformer of the components of the Type PHT-13 three-phase on-load tap-changer. Three single-phase selector switches *8* of phases *A*, *B* and *C*, and a current-limiting reactor *9* are

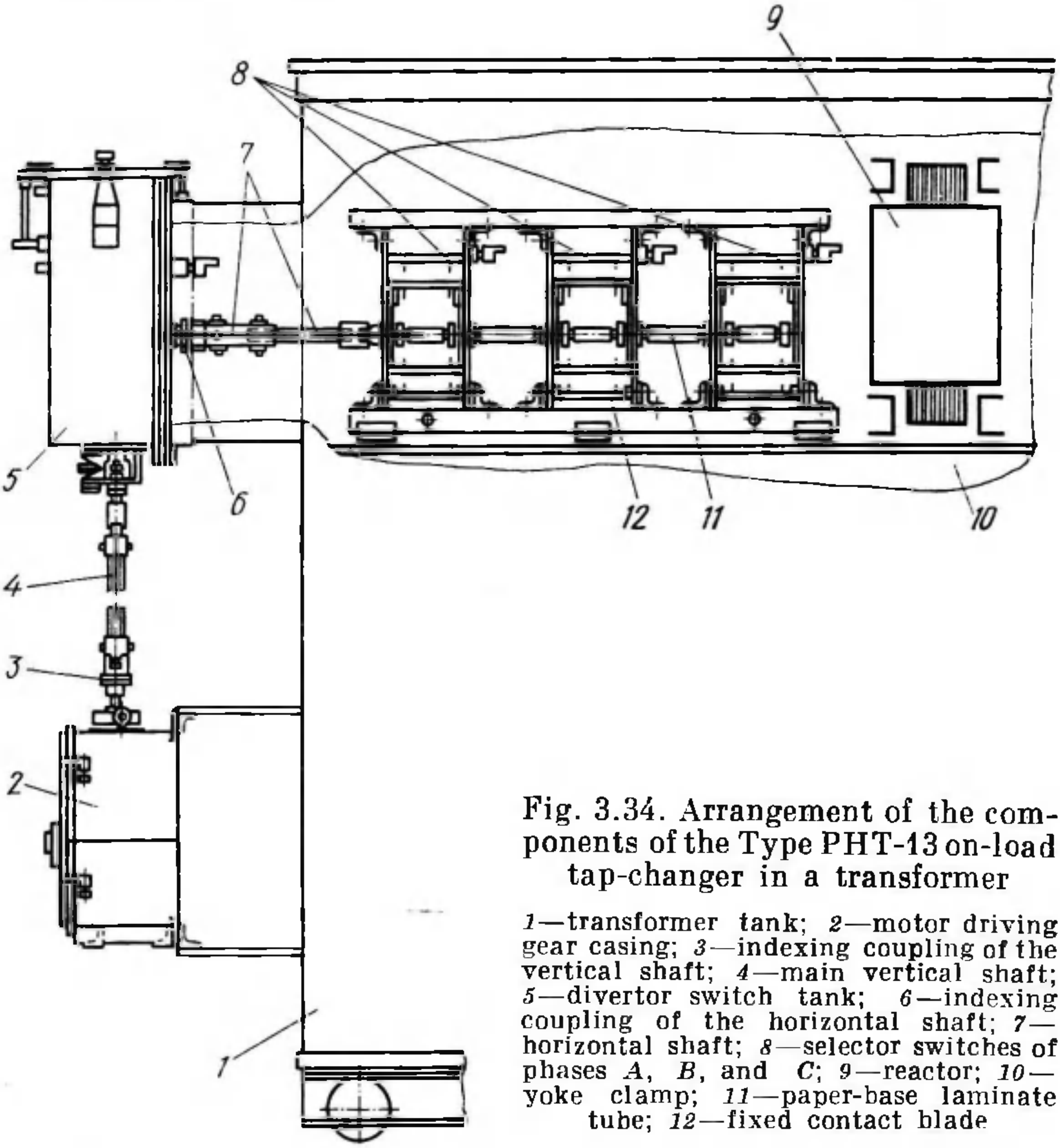


Fig. 3.34. Arrangement of the components of the Type PHT-13 on-load tap-changer in a transformer

1—transformer tank; *2*—motor driving gear casing; *3*—indexing coupling of the vertical shaft; *4*—main vertical shaft; *5*—divertor switch tank; *6*—indexing coupling of the horizontal shaft; *7*—horizontal shaft; *8*—selector switches of phases *A*, *B*, and *C*; *9*—reactor; *10*—yoke clamp; *11*—paper-base laminate tube; *12*—fixed contact blade

installed on the top yoke clamps *10*. The selector switches are ganged up by means of paper-base laminate tubes (insulating couplings) *11*. The operation of the divertor switches (see Fig. 3.33) involves the breaking of current, which causes arcing at the switch contacts. Therefore, the switches are mounted in an oil-filled tank *5* separate from the main

transformer tank *1* so as to avoid contamination of the main body of oil due to the arcing at the switch contacts. In addition, this enables one to inspect and repair the divertor switches without opening up the main transformer tank.

The selector and divertor switches are actuated by an operating mechanism driven from a driving gear housed in a casing *2* which is mounted on the main transformer tank. The driving gear can be actuated both manually (with a handle) and by a motor provided with a push-button control. The operating mechanism is so arranged that the selector and divertor switches of all the phases operate simultaneously in the sequence described above (see Fig. 3.33). The divertor switches of all the phases are assembled into two groups so that one group contains all the switches of even serial numbers and the other, those of odd serial numbers.

In the Type PHT-13 tap-changer, the main vertical shaft *4* of the operating mechanism makes a complete revolution per change, which occupies about 3 seconds. The operating mechanism is equipped with a signalling system and an operation counter. The motor driving gear is usually controlled remotely, so the remote position indicators are installed on a remote-control panel.

Prior to putting a newly repaired transformer into operation. the sequence of the opening and closing of the selector and divertor switch contacts is checked by plotting what is known as the circle diagram.

On-Load Tap-Changers Using Current-Limiting Resistors. Lately, quick-action on-load tap-changers fitted with current-limiting resistors have found wide application in transformer engineering in this country. The principle of operation of such tap-changers is illustrated in Fig. 3.35. Like the tapping switches using current-limiting reactors, these tap-changers consist of a selector switch, divertor switch(es), current-limiting impedance (which in this case is resistive), operating mechanism driven from a motor driving gear equipped with a control system, and signalling system.

In the normal operating position on tap *II* (Fig. 3.35*a*), divertor switches *DS1* and *DS2* are open, while switches *DS3* and *DS4* are closed. Thus, resistor *R2* is short-circuited and the load current I_l flows from tap *II* to the neutral or a line terminal via a selector switch contact *SC2* closed on

this tap and the closed contacts of the divertor switch *DS4*. In this position, an odd-step selector switch contact *SC1*

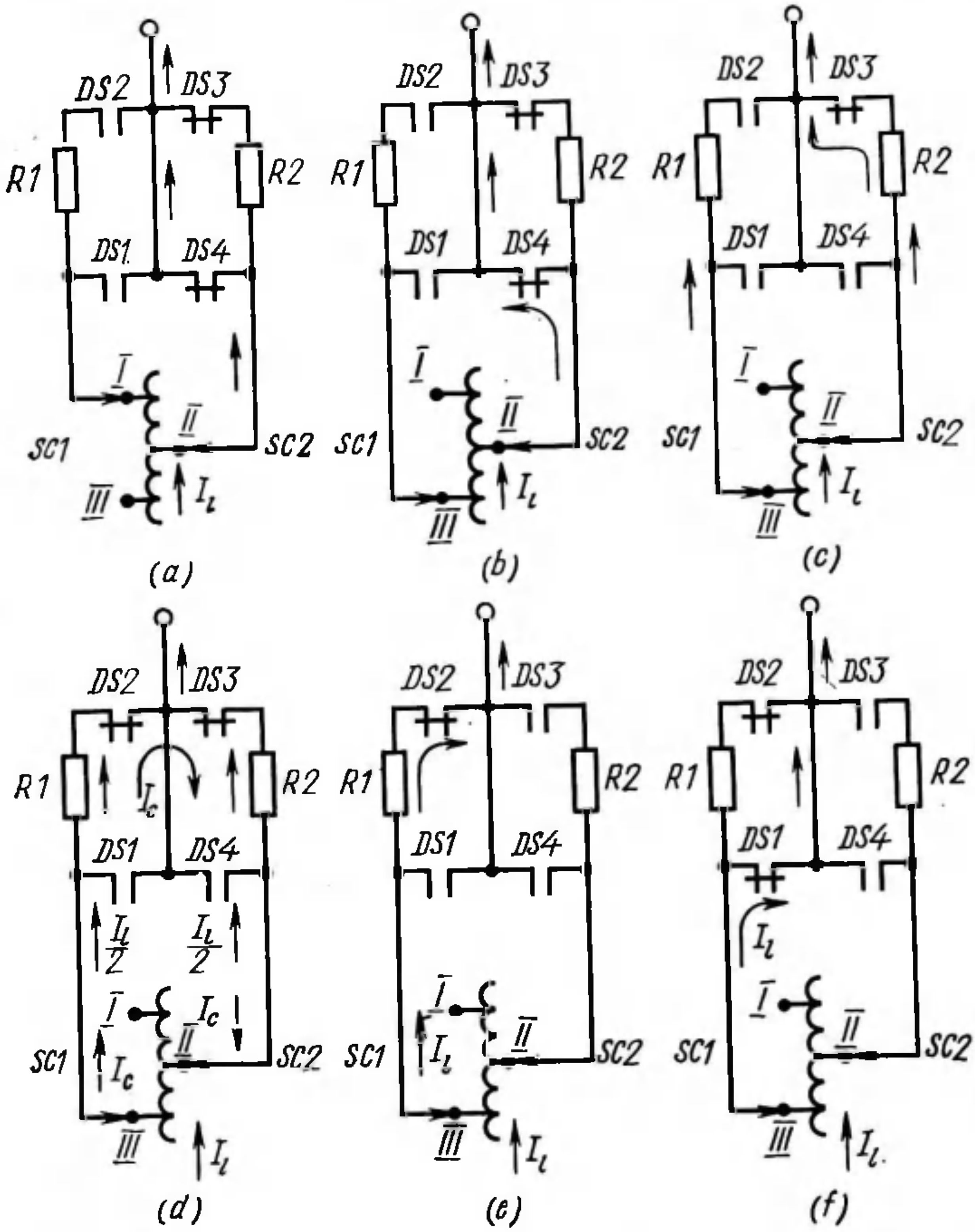


Fig. 3.35. Elementary diagram of an on-load tap-changer using current-limiting resistors

(*a*) through (*f*) complete tap-changing cycle

is off-circuit and is awaiting a command from the operating mechanism to move either to tap *I* or to tap *III*.

If it is desired to change to tap *III*, the operating mechanism is actuated in the direction of increasing ordinal numbers

of the voltage steps. First, the selector switch contact *SC1* closes on tap *III* (Fig. 3.35*b*), then the divertor switch *DS4* opens (Fig. 3.35*c*) and the load current flows through the resistor *R2*. Thereafter, the divertor switch *DS2* closes (Fig. 3.35*d*), thereby bringing the tap-changer into the bridging position, and the load current divides equally between resistors *R1* and *R2*. At the same time, the voltage across the tap winding *II-III* is impressed on the resistors and causes a circulating current I_c to flow through the impedance loop formed by the tap winding and resistors. Then the divertor switch *DS3* opens (Fig. 3.35*e*) and the load current flows through the resistor *R1*. After that, the divertor switch *DS1* closes and short-circuits the resistor *R1*, thus completing the tap-changing cycle; the transformer now operates on tap *III* (Fig. 3.35*f*). When changing to the next tap, the selector and divertor switches operate in a similar sequence.

In on-load tap-changers using current-limiting resistors, the tap-changing cycle continues for a few hundredths of a second, the divertor switches being opened and closed almost instantly by the stored energy of powerful springs.

As compared with the on-load tap-changers fitted with current-limiting reactors, those with resistors have the advantage that they occupy relatively less bulk (the bulky, powerful reactor is replaced by small-size resistors) and incorporate a stored energy device (spring drive), so that transition from one tapping to another can be completed even if the supply to the driving motor should be interrupted, thereby protecting the resistors from failing in an intermediate (bridging) position of the mechanism. Also, such tap-changers are more easy to install in the transformer (installed as a single whole inside the transformer tank near one of its end walls). On the other hand, their construction is much more complex than that of the tap-changers with reactors, because the high operational speeds require that the mechanisms used should be highly reliable and accurate so as to ensure the correct sequence of operation of the contact system.

Three-phase on-load tap-changers with current-limiting resistors are obtained by ganging up three single-phase switches in a single unit having the shape of a column. The selector and reversing switches are installed at the bottom

of the column, with the divertor switches and resistors mounted higher up. The divertor switches are separated from the selector switches by a paper-base laminate cylinder which not only doubles as an insulating and a supporting structure, but also separates the oil in the divertor switch compartment from the main body of oil. The cylinder is fixed to a steel flange which is mounted on the transformer tank cover, an oil-sealing gasket being placed between the flange and cover. It is advisable to study the construction of such a tap-changer in detail while directly participating in disassembly operations involved in actual transformer repair work.

3.6. The Leads

Leads are various conductors used for connecting the winding ends to one another and to the terminal bushings, and the voltage-control taps to the tap-changer, and also for making other connections inside the transformer. The leads connecting the windings to the terminal bushings are called *line* or main, while those connecting the voltage taps to the tap-changer are referred to as *regulating*. Round and rectangular (strip) copper and aluminium conductors and stranded (flexible) cables are used for making the leads.

In Size I through III transformers for voltages up to 525 V, the leads are, as a rule, not insulated. Leads up to 5.2 mm in diameter for voltages from 6 to 35 kV are insulated with cable paper, while those of a larger diameter, with paper-base laminate tubes. Size IV transformers for voltages from 6 to 35 kV have their leads made from Grade ПБОТ stranded cable. Leads for 110 kV and higher voltages are insulated with varnished cloth and crepe paper. The cross-sectional area of leads depends on the current to be handled, insulation thickness, and cooling conditions. The permissible current density for insulated leads is somewhat less than for bare leads. On the average, it ranges from 2.5 to 4.8 A/mm^2.

If insulated leads are covered by the elements of their support structure, the permissible current through them is reduced. Table 3.2 gives the permissible current in oil-immersed paper-insulated copper conductors as a function of their insulation thickness, and also, the percent reduction

Table 3.2

Permissible Current in Oil-Immersed Paper-Insulated Copper Conductors as a Function of Insulation Thickness (at 20°C Conductor Rise over Oil)

<table>
<tr><th rowspan="3">Conductor section, mm²</th><th rowspan="3">Bare conductor diameter, mm</th><th colspan="3">Insulation thickness, mm</th><th rowspan="3" colspan="2">Remarks</th></tr>
<tr><th>3</th><th>6</th><th>8</th></tr>
<tr><th colspan="3">Permissible current, A</th></tr>
<tr><td>16</td><td>5.8</td><td>80</td><td>—</td><td>—</td><td colspan="2" rowspan="6">If the surface of conductors is covered by supporting cleats, the permissible current in them should be reduced as indicated below</td></tr>
<tr><td>25</td><td>7.7</td><td>125</td><td>125</td><td>118</td></tr>
<tr><td>50</td><td>10.2</td><td>236</td><td>195</td><td>184</td></tr>
<tr><td>95</td><td>14.3</td><td>364</td><td>298</td><td>270</td></tr>
<tr><td>150</td><td>18.1</td><td>505</td><td>409</td><td>382</td></tr>
<tr><td>240</td><td>23.0</td><td>705</td><td>566</td><td>530</td></tr>
<tr><td>300</td><td>26.2</td><td>827</td><td>661</td><td>—</td><td>Surface coverage, %</td><td>Current reduction, %</td></tr>
<tr><td>400</td><td>29.8</td><td>1025</td><td>—</td><td>—</td><td>10</td><td>5</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>20</td><td>10</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>30</td><td>16</td></tr>
</table>

of the permissible current in leads as a function of the percent coverage of their surface by supporting cleats.

When arranging the leads in a transformer, one should maintain certain definite creepage distances which depend on voltage, insulation thickness of the leads, and surrounding medium (oil or air). The main creepage distances are the distance between a lead and the nearest earthed part, the distance between a lead and a winding, and the distance between leads at different voltages.

Table 3.3 lists the standard creepage distances between the leads and earthed parts in oil-immersed transformers.

The leads are connected to windings and to one another by brazing or soldering (some transformers use bolted connections). The lead end to be connected to a terminal bushing or to a terminal stud of the tap-changer is given an expans-

Table 3.3

Standard Creepage Distances between Leads and Earthed Parts in Oil-Immersed Transformers

Voltage class, kV	One-side insulation thickness, mm	Creepage distance, mm	
		from leads to earthed parts of angular shape	from leads to earthed parts of flat shape
3 and 6	2	10	10
10	2	12	10
35	4	37	30
110	20	160	75

ion bend or is fitted with a flexible connector made up of a set of copper ribbons. Such flexible connections (Fig. 3.36) protect the leads and bushings against deformations due to

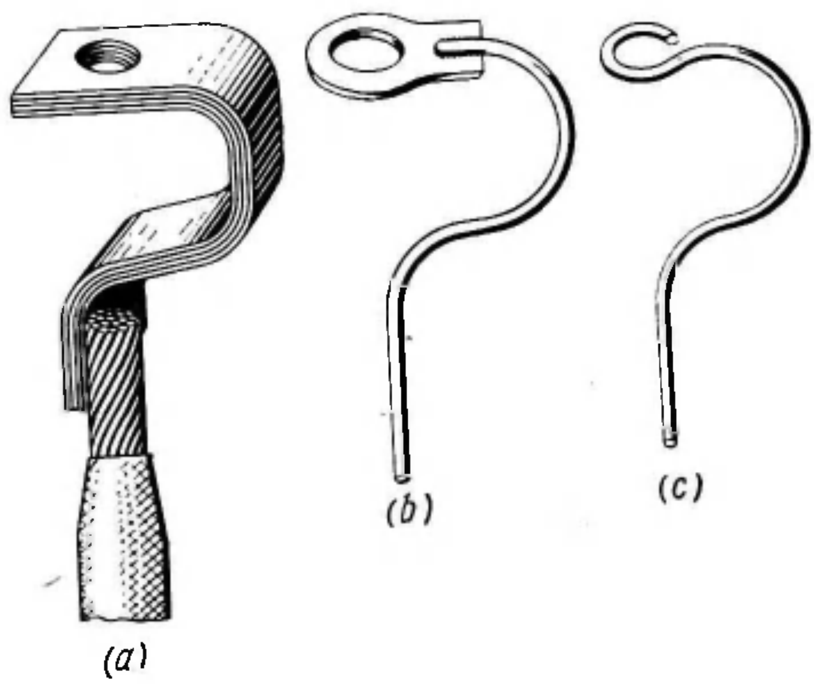


Fig. 3.36. Lead terminations

(*a*) flexible connector of copper ribbons; (*b*) lead end with an expansion bend and a tag; (*c*) looped lead end with an expansion bend

dynamic forces in the event of a short circuit and, at the same time, compensate for possible differences in the lead length when assembling the transformer. The cross-sectional area of the copper ribbons and their number in a flexible connector are selected so as to ensure that the current density in the connector does not exceed 4.8 A/mm^2.

When current flows through adjacent leads, mechanical forces develop between them. If the currents in the leads flow in the same direction, tne leads tend to attract, while if the currents are in opposite directions, the leads tend to repel. The forces acting between the leads grow especially great in the event of a short circuit. Also, heavy-gauge leads have a substantial mass. All this requires that the leads

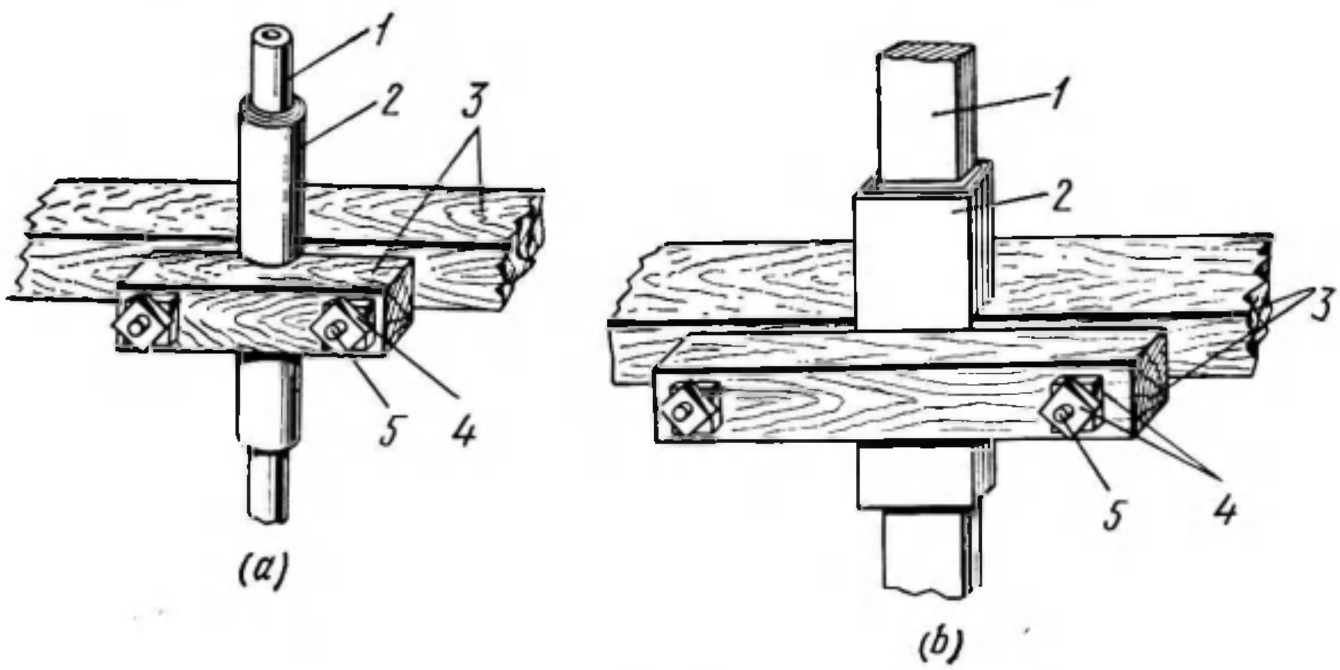


Fig. 3.37. Fixing of leads with beechwood cleats

(*a*) round lead; (*b*) bus (strip) lead; *1*—lead; *2*—additional insulation; *3*—cleats; *4*—nuts; *5*—studs

should be reliably fixed in place. The leads are fixed by means of beechwood cleats (Fig. 3.37). A lead *1* is placed between cleats *3* which are clamped by bolts or studs *5*. Where the leads are fixed in the vicinity of the windings, clamping studs made of beechwood or fabric-base laminate (which is mechanically stronger) and plastic nuts are used, whereas in the zone outside the windings the lead-supporting cleats are clamped with metal bolts. The entire wooden construction that carries the leads is called the lead support structure. It is held to the yoke clamps by steel bolts. Fig. 3.38 illustrates the fastening of the LV leads in the Type TM-6300/35 transformer.

The wooden parts of the lead support structure must he dry and strong, and must have a smoothly plained surface. The most popular cleats are 20 mm by 30 mm, 20 mm by

40 mm, 30 mm by 40 mm, 40 mm by 40 mm, 40 mm by 50 mm, 50 mm by 50 mm, and 50 mm by 70 mm in section. Where they are clamped between the cleats, the leads are given an additional insulation *2* (see Fig. 3.37) in the form of concentric layers of roll pressboard or cable paper. The

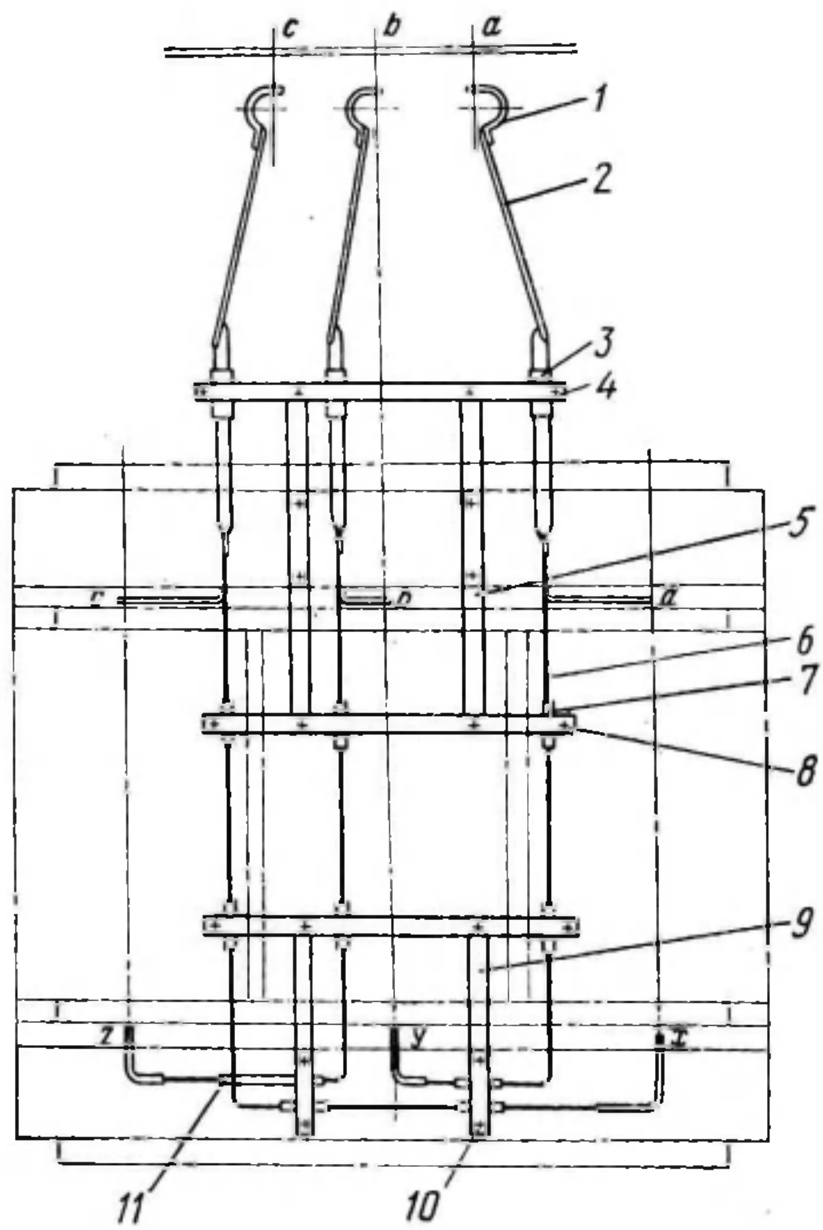


Fig. 3.38. Fastening of the LV leads with beechwood cleats in the Type TM-6300/35 transformer

1—flexible connector; *2*—LV line lead; *3* and *7*—pressboard insulation; *4*, *5*, and *9*—beechwood cleats; *6*—copper conductor; *8*—fabric-base laminate stud and nut; *10*—steel stud and nut and washer; *11*—paper-base laminate tube

thickness of the additional insulation is from 3 to 4 mm on one side for voltages from 6 to 35 kV and 8 mm for 110 kV.

A failure to keep to the design creepage distances along wooden insulation between adjacent leads or between leads and earthed parts may result in a flashover. The standard creepage distances for wooden insulation are given in Table 3.4.

Table 3.4

Standard Creepage Distances for Wooden Insulation

Voltage class, kV	One-side lead insulation thickness, mm	Creepage distance, mm	
		from leads to earthed parts	from leads to floating (unearthed) parts
3 and 6	2	30	25
10	2	40	25
35	4	100	70
35	6	80	55
110	20	380	—

3.7. Terminal Bushings

The transformer windings are connected to the external circuit through *terminal bushings*—porcelain through insulators with a central conductor or terminal. The bushings are installed on the cover or, more seldom, on a side wall of the transformer tank. The lower ends of the bushings fit into the tank, while their other ends project above the tank cover, and the terminals at both their ends are provided with suitable fasteners to connect the line leads inside the transformer and external circuit conductors outside it.

The shape and size of the terminal bushings depend on the voltage class, type of service (indoor or outdoor), and rated current. Indoor bushings have a plain outer surface and are relatively small in size. Outdoor bushings which in service are subjected to adverse atmospheric effects (rain, snow, contaminated air), differ from the indoor type in that they are provided with umbrella-shaped watersheds or skirts that materially extend their outer surface. The watersheds increase the creepage distance along porcelain, thereby improving the electric strength of the bushings. At present, all power transformers use outdoor bushings.

Terminal bushings are available for voltages of 0.5, 1, 3, 6 to 10, 20, 35, 110, 220, 330, 500 and 750 kV. Power transformers for 3 and 6 kV use 10-kV bushings.

Permanent (Nondetachable) Bushings

Figure 3.39 shows a permanent terminal bushing for voltages from 6 to 10 kV. Such bushings are used in old transformers manufactured in the pre-war period, and when repairing such transformers, the bushings have to be either re-cemented or replaced altogether. The bushing consists of a porcelain insulator *1* which separates the terminal *2* from the tank cover *9*, a cap *4* which centres the terminal and into which the top end of the insulator is cemented, a round metal flange *5* which is made fast to the insulator by means of special cement *10* and serves for mounting the bushing on the transformer tank cover, a steel washer *8*, and a pressboard washer *7* which has a cut-out to permit the oil in the transformer tank to enter the inner space of the bushing. All the components of the bushing are held together by the terminal.

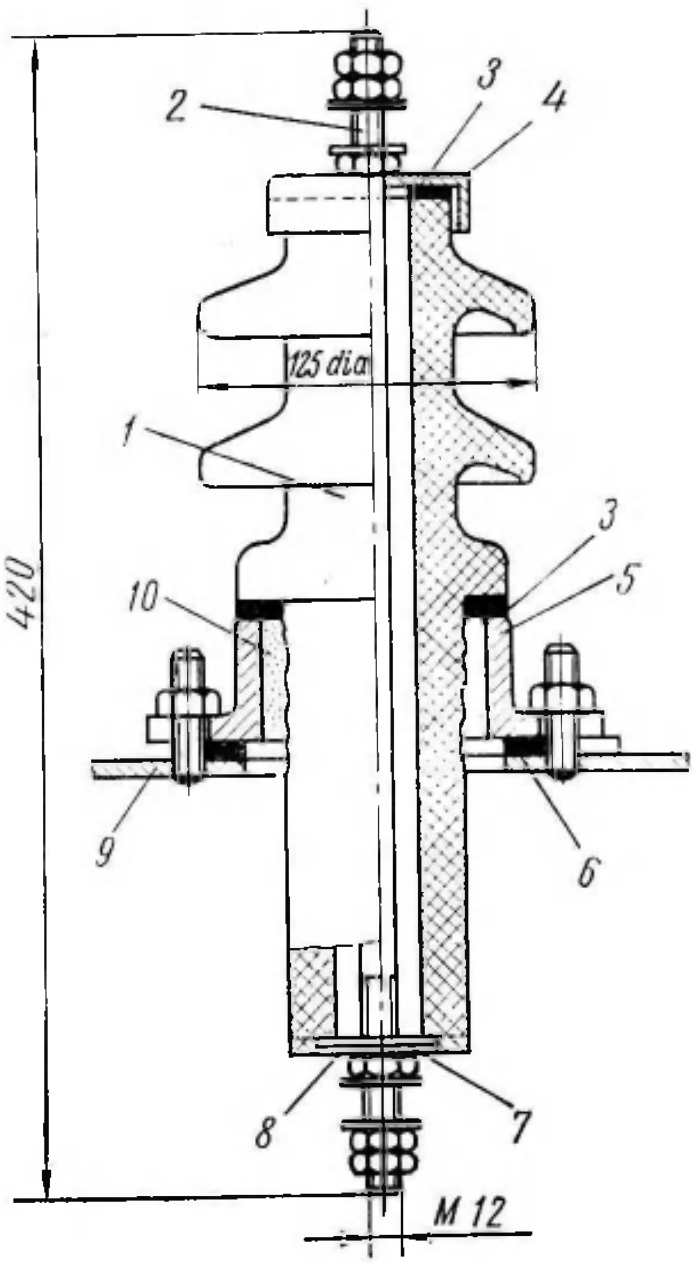


Fig. 3.39. Permanent terminal bushing for 6 to 10 kV at 275 A

1—porcelain insulator; *2*—copper terminal and nuts and washers; *3*—rubber gaskets; *4*—cap; *5*—flange; *6*—gasket; *7*—pressboard washer; *8*—steel washer; *9*—transformer tank cover; *10*—cement

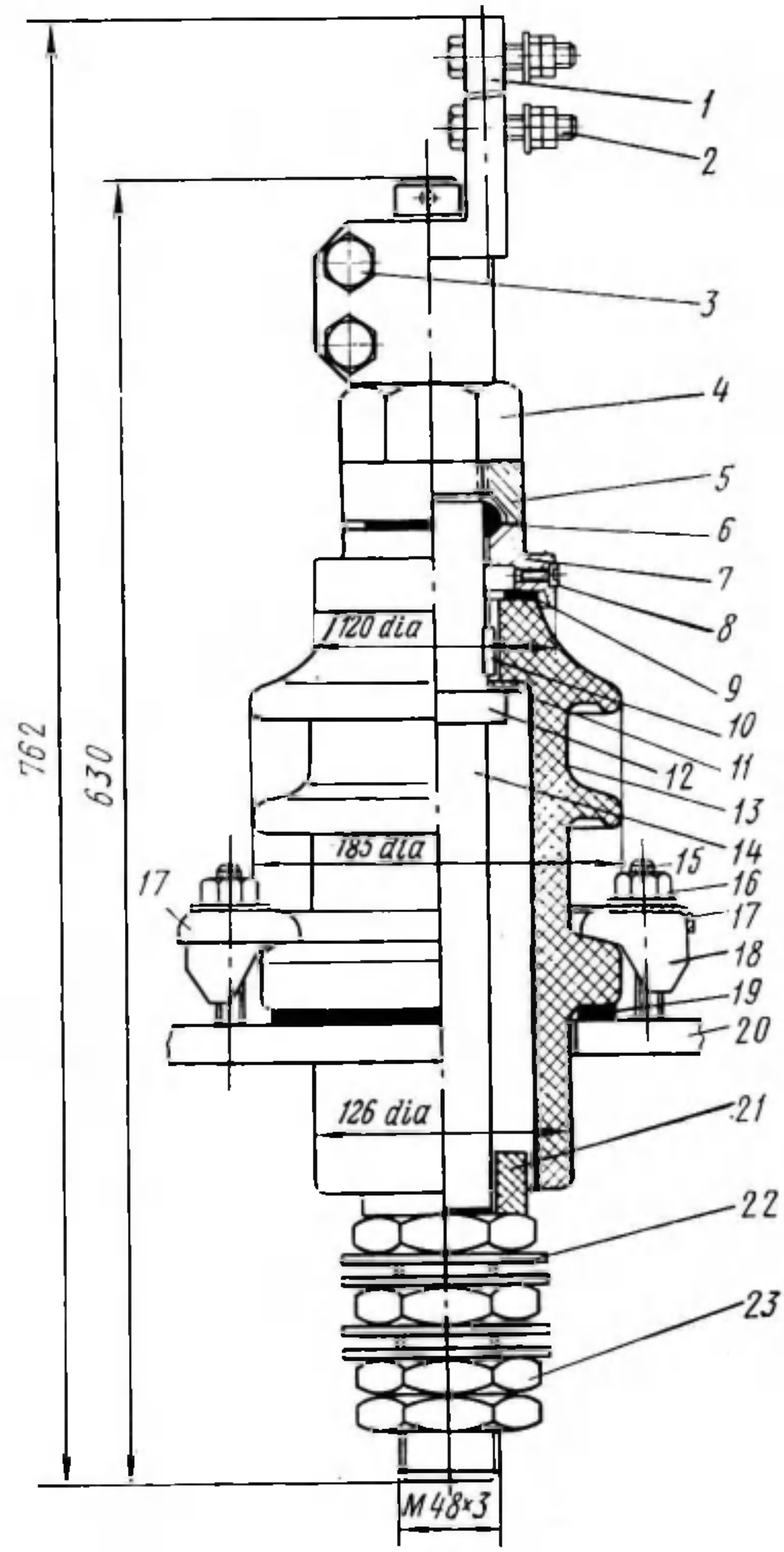
To prevent oil leakage from the top part of the bushing, the threaded joint between the cap and terminal is soldered all around and a rubber gasket *3* is placed between the end face of the insulator and the cap. Oil leakage through the flange-to-cover joint is prevented by placing a sealing gasket *6* between them and tightening the joint by nuts.

Permanent terminal bushings are difficult to manufacture and repair, and also, are not very reliable in service, because of a relatively rapid ageing of the cement. Besides, much oil has to be drained from the tank when a faulty bushing is to be replaced. Ahother disadvantage of this type of bushing is that special holes have to be made in the transformer cover for connection of the leads to the bushings, and where such holes are not provided (Size I through III transformers) and the core-coil unit is attached to the cover, the entire assembly has to be removed from the tank to disconnect the leads and repair the bushings.

Detachable (Knock-down) Bushings

Newly manufactured transformers for voltages up to 35 kV inclusive are equipped with detachable terminal bushings which are free from the drawbacks of the permanent-type bushings. Fig. 3.40*a* shows a detachable terminal bushing for voltages from 6 to 10 kV at 3 000 A. The terminal *14* of the bushing is sealed in its upper part by a rubber O-ring *6* and a washer *9* (usually rubber) compressed by a nut *4*. The shoulder *12* of the terminal rests against the matching shoulder of a porcelain insulator *13*, a pressboard washer *11* being placed between the shoulders. The terminal is provided with two projections *10* which fit into the corresponding recesses in the insulator to prevent the terminal from turning in the insulator when tightening the nuts screwed on the terminal.

The terminal is connected to the external circuit by means of a contact lug *1* fitted with bolts *2* (and the associated nuts and washers), which is screwed on the terminal and clamped in place by bolts *3* (the threaded portion of the contact lug is split). Where currents are less than 800 A, common nuts and washers are used on the terminal in place of the contact lug. The lower part of the terminal is centred in the insulator by means of a paper-base laminate sleeve *21* and is fitted with washers *22* and nuts *23* for connection of the flexible lead connectors inside the tank. A screw *8* fitted in the brass cap *7* serves for bleeding air from the bushing when it is being filled with oil.



(a)

Fig. 3.40. Detachable (knock-down) terminal bushings

(*a*) for 6 to 10 kV at 3 000 A; (*b*) for 35 kV at 600 A; *1*—contact lug; *2*—bolt and nuts and washers; *3*—clamping bolt; *4*—special nut; *5*—brass sleeve; *6*—rubber O-ring; *7*—brass cap; *8*—air-bleed screw; *9*—rubber washer; *10*—terminal projection; *11*—pressboard washer; *12*—terminal shoulder; *13*—porcelain insulator; *14*—copper terminal; *15*—steel stud; *16*—steel nut; *17*—pressed flange; *18*—catch; *19*—rubber gasket; *20*—transformer tank cover; *21*—paper-base laminate sleeve; *22*—copper washer; *23*—brass nut; *24*—steel bolt; *25*—mounting flange welded to the tank cover; *26*—paper-base laminate tube

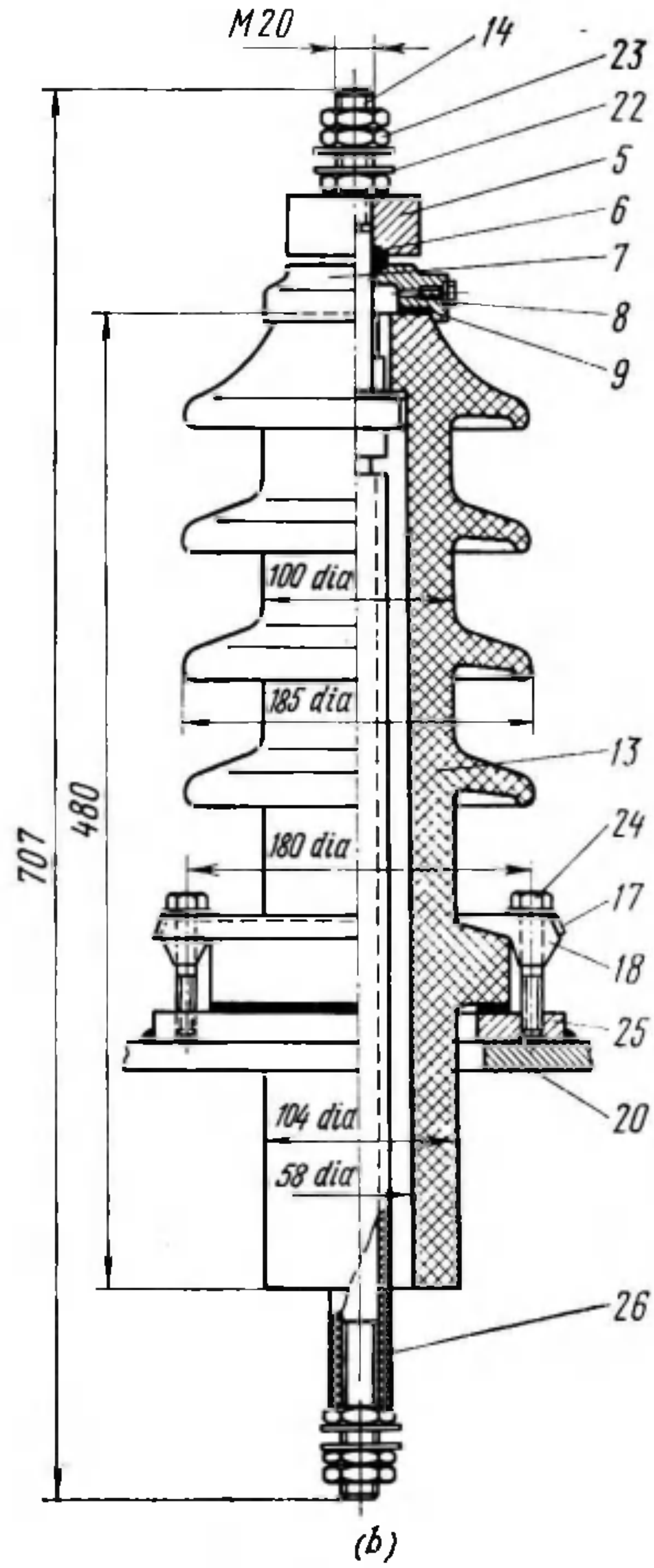


Fig. 3.40. (*b*)

The bushing is held to the transformer tank cover *20* by catches *18*. A flange *17* retains the catches on the insulator flange.

Figure 3.40*b* shows a detachable terminal bushing for 35 kV at 600 A. The terminal *14* of the bushing is additionally insulated with a paper-base laminate tube *26*, and the porcelain insulator has a greater number of watersheds. When

filling up the tank, the oil freely enters the bushing (screw *8* should be backed off beforehand).

The main advantage of the knock-down bushings is that they readily lend themselves to repair: there is no need to disconnect the leads inside the tank, or withdraw the core-coil assembly from the tank, in order to replace a faulty bushing. For instance, to replace the porcelain insulator *13* and its sealing gasket *19* (see Fig. 3.40*a*), the only thing to do is to back off bolts *3*, unscrew contact lug *1* and nut *4* off the terminal, remove sleeve *5*, O-ring *6* and brass cap *7*, unscrew nuts *16* off the studs *15* installed on the tank cover, and remove catches *18*. Then the insulator is replaced by a new one fitted with a set of new rubber gaskets, and the bushing is re-assembled.

The flow of a heavy current (of the order of hundreds and thousands of amperes) through the terminal of the bushing gives rise to a strong magnetic flux around the bushing, and the eddy currents produced by this flux in the steel bushing flange and tank cover may heat them to a prohibitively high temperature. To avoid this, brass and other materials of low magnetic permeability are used to make the bushing flanges where heavy currents are to be dealt with.

Another method to reduce the heating of the tank cover is to make a common opening in the cover for several terminal bushings (e.g., for LV bushings), or to cut slots between separate openings for the bushings and then weld the slots up with a diamagnetic electrode. In this case, the magnetic fluxes of all the bushings must have their paths around the common opening. If the bushings mounted in a common opening are connected to the start and finish of one and the same winding, there will be no flux surrounding both bushings in the cover, because the currents in the terminals will be equal in magnitude and opposite in direction, and their resultant magnetic flux will be practically zero. If the three line terminal bushings of a three-phase transformer are mounted in a common opening, there will be no magnetic flux around the bushings either, because the sum of the instantaneous values of currents in a three-phase system is equal to zero.

Figure 3.41 illustrates some methods of installing heavy-current terminal bushings for voltages from 0.5 to 10 kV.

The 525-volt bushings rated at 1200 A are installed in a common opening in the tank cover, in a cast-brass holder provided with as many pockets as there are bushings (Fig. 3.41*a*). The bushings *3* are directly cemented into the pockets of the holder *1* that is fastened to the tank cover *2*

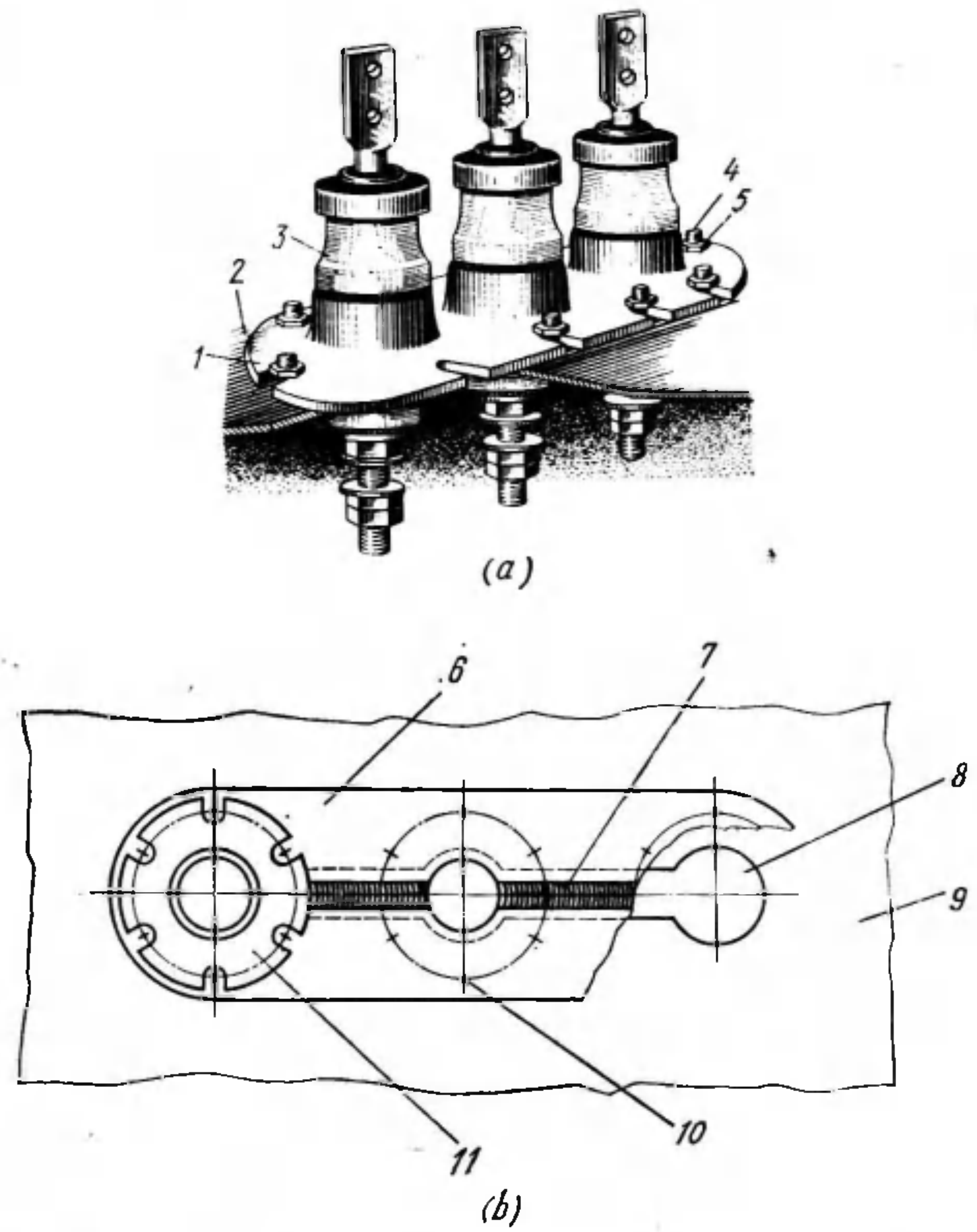


Fig. 3.41. Methods of installing heavy-current terminal bushings

(*a*) for 690 V at 1 200 A; (*b*) for 6 to 10 kV at more than 1 200 A

by means of studs *4* and nuts *5*, a sealing gasket being placed between the holder and cover. The bushings for voltages from 6 to 10 kV, rated at currents in excess of 1200 A, are mounted on a flat steel plate *6* (Fig. 3.41*b*) which is either bolted or welded to the tank cover *9* provided with a shaped

recess *8*. The plate has slots cut in it between the holes for the bushings, which are filled up with a diamagnetic metal *7*, this being achieved by welding the slots up with a stainless-steel electrode. The threaded holes *10* in the plate serve for fixing brass flanges *11*.

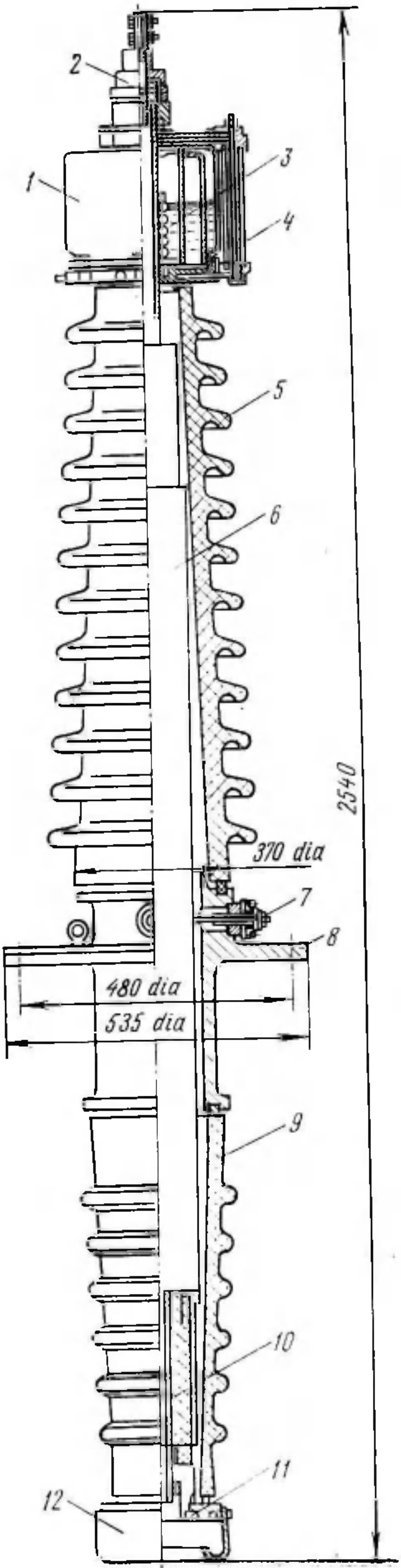
The terminal diameter of the bushings used in oil-immersed transformers is related to the maximum permissible current through them as follows.

Maximum permissible current, A	275	400	600	800	1 200	1 400	2 000	3 000
Metric thread for terminals of corresponding diameters	M12	M16	M20	M24	M30	2M33×1.5	M42	M46

Oil-Barrier and Oil-Impregnated-Paper Terminal Bushings

Terminal bushings for voltages of 110 kV and higher (USSR Standard 10693—63) may be of two types—oil-barrier (МБТ) and oil-impregnated-paper (БМТ). The major insulation in the Type МБТ bushings is transformer oil divided into concentric layers by paper-base laminate cylinders provided with electrostatic shields of aluminium foil. In the Type БМТ bushings, the insulating core is formed by tightly wound oil-impregnated cable paper divided into concentric layers by electrostatic shields of foil.

Like the Type МБТ bushing, the Type БМТ has a metal central tube *10* (Fig. 3.42) which joins together all the main bushing components—an oil-barrier core *6*, top and bottom porcelain shells *5* and *9*, a coupling bush *8*, a contact lug *2*, etc. In most terminal bushings for voltages from 110 to 120 kV, the current-carrying element is a flexible conductor passing through the central tube from the windings to the contact lug. Terminal bushings for voltages of 110 kV and higher are filled with transformer oil not communicating with the main body of oil in the transformer tank.



Old terminal bushings of the oil-barrier type were equipped with a glass expansion chamber and a breather to make the chamber communicate with the atmosphere. Modern oil-filled bushings Types БМТ and МБТ have a metal expansion chamber equipped with a liquid-type (oil) seal. The seal protects the oil from moisture and mechanical impurities contained in the surrounding air, while the metal walls of the expansion chamber provide protection against the harmful effects of sunrays.

Hermetically-Sealed Terminal Bushings

Lately, on voltages of 110 kV and higher, wide application have found what is known as hermetically-sealed terminal bushings. These differ from the Type БМТ in that the oil contained in them does not communicate with the atmosphere; they have no expansion chamber and liquid seal. Their internal insulation together with the core is enclosed

Fig. 3.42. Oil-impregnated-paper flangeless terminal bushing for 110 kV at 600 A

1—metal expansion chamber with an oil seal; *2*—brass contact lug; *3*—compensating spring of the tightening device; *4*—oil gauge; *5*—top porcelain shell; *6*—core; *7*—test terminal; *8*—coupling bush; *9*—bottom porcelain shell; *10*—central tube; *11*—oil-drain hole; *12*—electrostatic shield

in porcelain shells filled with deaerated transformer oil under pressure.

To compensate for temperature changes in the oil volume, use is made of a separate oil-filled pressure tank communicating with the bushing via an annealed-copper tube. The compensation is effected by a set of separate compensating elements (bellows) installed in the pressure tank. The elements are shaped as hollow disks of thin tin plate, and are filled with an inert gas—nitrogen or argon. As the oil volume increases with temperature, the disks somewhat flatten under the pressure of the surrounding oil, thus decreasing in volume, whereas when the temperature drops down, the volume of the oil in the pressure tank decreases and the disks grow in volume, because of the difference in pressure between the gas enclosed in the disks and the oil in the tank. The temperature changes of the pressure in the bushing-pressure-tank system must follow the pressure-versus-ambient-temperature curve given in the specifications for a given type of bushing. The oil pressure in the bushing is monitored by means of a compound gauge fitted on a special valve provided for the purpose on the coupling bush.

The 110- and 120-kV hermetically-sealed bushings of the latest designs are equipped with a compensating device installed directly at the bushing head, so there is no need for them to have separate pressure tanks.

Hermetically-sealed terminal bushings are reliable in operation, and are intended for use in conditions of both normal and severe atmospheric pollution and also, in climatic conditions of the torrid zone.

3.8. Transformer Insulation

In service, the windings and other current-carrying parts of the transformer are subjected to the operating voltage of the line. Also, they may be subjected to various overvoltages. Therefore, all these parts must be reliably insulated both from one another and from earthed parts.

The insulation of oil-immersed transformers is classified as *internal* and *external*. The internal insulation is that which is placed inside the transformer tank (i.e., oil-immersed insulation) and the external insulation is the one outside the tank (i.e., air-immersed insulation).

Internal Insulation

This comprises the major and minor insulation of the windings and also, the insulation of the tap-changing arrangements and leads.

Major Insulation. The major insulation is that which insulates the windings from one another and from earthed parts,

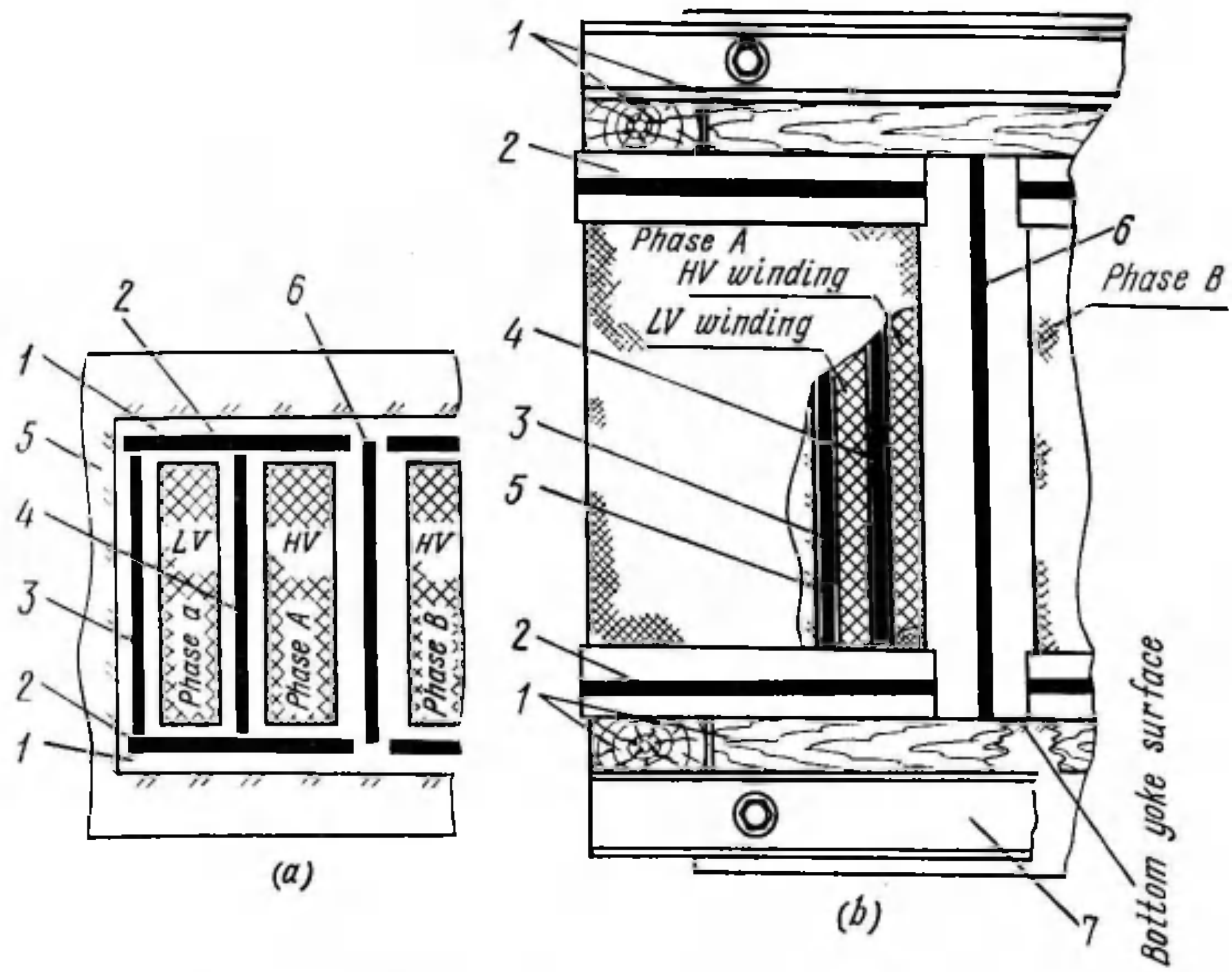


Fig. 3.43. Major insulation of Size I and II transformers

(a) insulation diagram of phase A windings; (b) arrangement of the insulation components of phase A windings in a transformer

such as the core and tank. Figure 3.43 shows the major insulation of Size I and II transformers. The LV winding is insulated from the core limb *5* (Fig. 3.43*a*) by an oil space (duct) and an insulating cylinder *3*. A similar cylinder *4* is installed between the HV and LV windings.

The cylinders *3* and *4* may be in the form of either pressboard sheets wrapped directly around the core limb and the LV winding or ready-made paper-base laminate cylinders in-

cluded in the winding set. In the former case the cylinders are called soft, and in the latter, rigid. The wall thickness of the cylinders depends mainly on the voltage class of the windings, ranging between 1.5 and 2.5 mm at voltages up to 15 kV and between 4 and 6 mm at voltages from 35 to 110 kV. Between the HV windings of different phases there is an interphase insulation *6* which in transformers for voltages up to 35 kV is a 2 to 3 mm thick pressboard barrier fixed either to the yoke clamps or vertical tie-rods.

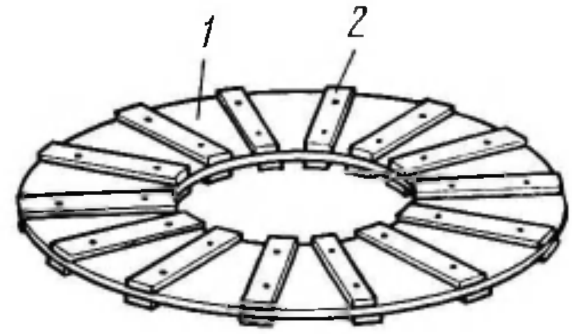


Fig. 3.44. Yoke insulation of a winding

The windings are insulated from the top and bottom yokes by the yoke insulation *2* which is placed between the top and bottom end faces of the coils and the coil-end insulation *1*. The yoke insulation pattern varies with different transformers, especially for Size I and II transformers. Figure 3.44 shows a yoke insulation which is a 2 to 3 mm thick annular pressboard disk *1* having spacing blocks *2* fixed to it from either side. The blocks are intended to form the necessary oil ducts between the yokes and windings.

The coil-end insulation *1* (see Fig. 3.43*b*) serves to make the surface of the top and bottom yoke clamps *7* flush with the horizontal surface of the yokes. In Size I and II transformers, the coil-end insulation is made in the form of a deck of beechwood planks (Fig. 3.45*a*) with recesses cut in them to allow the ends of the inner coils to be brought out and to provide for oil circulation. In some of the transformers for up to 15 kV, the wooden deck also doubles as the yoke insulation, with pressboard barriers being placed between the windings and yokes.

The coil-end insulation for transformers of 2 500 kV A and upwards is made of pressboard. Figure 3.45*b* shows the coil-end insulation for Size III three-phase transformers.

As the voltage class of the transformer grows higher, the requirement for the electric strength of its insulation becomes more demanding. One has to increase oil spaces and use various pressboard elements, such as cylinders, collars, and

barriers. It should be noted, however, that solely increasing the insulation clearances and pressboard thickness may worsen rather than improve the electric strength of the insulation. Therefore, great importance is attached not only to the correct choice of the physical dimensions for the insulation elements, but also to their proper placement.

The pattern of the transformer insulation varies with the type of the windings, arrangement of the voltage-control taps, and position of the point the line lead of the HV wind-

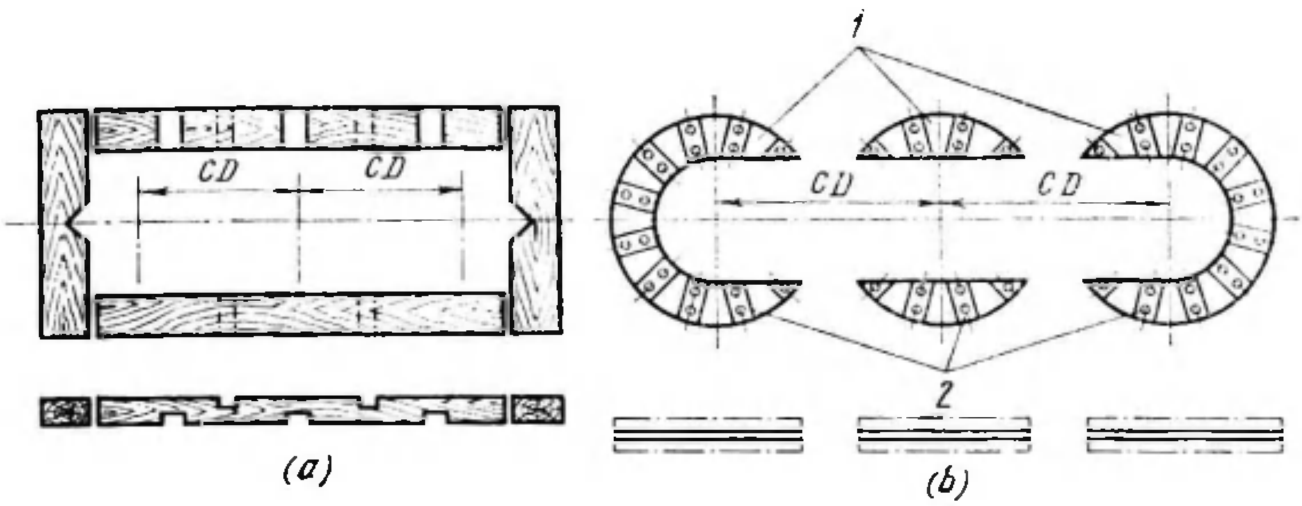


Fig. 3.45. Coil-end insulation of three-phase transformers

(a) in Size I and II transformers; (b) in Size III transformers; 1—pressboard plates; 2—pressboard spacers; CD—centre distance (the distance between the core limb axes)

ing is taken from (in the middle of the coil, at an end of the coil with the neutral point at its other end, with the neutral point in the middle of the coil, etc.).

Figure 3.46 shows the construction of the major insulation in a 110-kV three-phase transformer with the line lead taken from the top end of the winding and the neutral lead, from the bottom end. Insulating cylinders *1*, usually 6 mm in wall thickness, are made up of 1.5 to 2 mm thick pressboard sheets, and 8 mm thick collars *3* are assembled from 0.5 mm thick pressboard strips. To give the strips the necessary L-shape, they are split lengthwise in half from one end up to the bend, the slit in one strip being overlapped by the intact half of the next when assembling the collars. The collars serve to reinforce the insulation of the top portion of the HV coils in order to prevent flashover between the coils and the steel pressure rings and top yoke. The

interphase insulation (barrier) *4* consists of two 8 mm thick pressboard barriers with pressboard spacing blocks placed between them to form an oil duct. The purpose of the interphase insulation is to reliably insulate the adjacent phases from each other.

The major insulation also includes the end-winding insulation whose elements fill up the free spaces between the ends of the windings and yokes. The end-winding insulation comprises all the structures and elements that insulate the end turns of the windings from the yokes, yoke clamps, and pressure rings, the chief structures being the yoke and coil-end insulation.

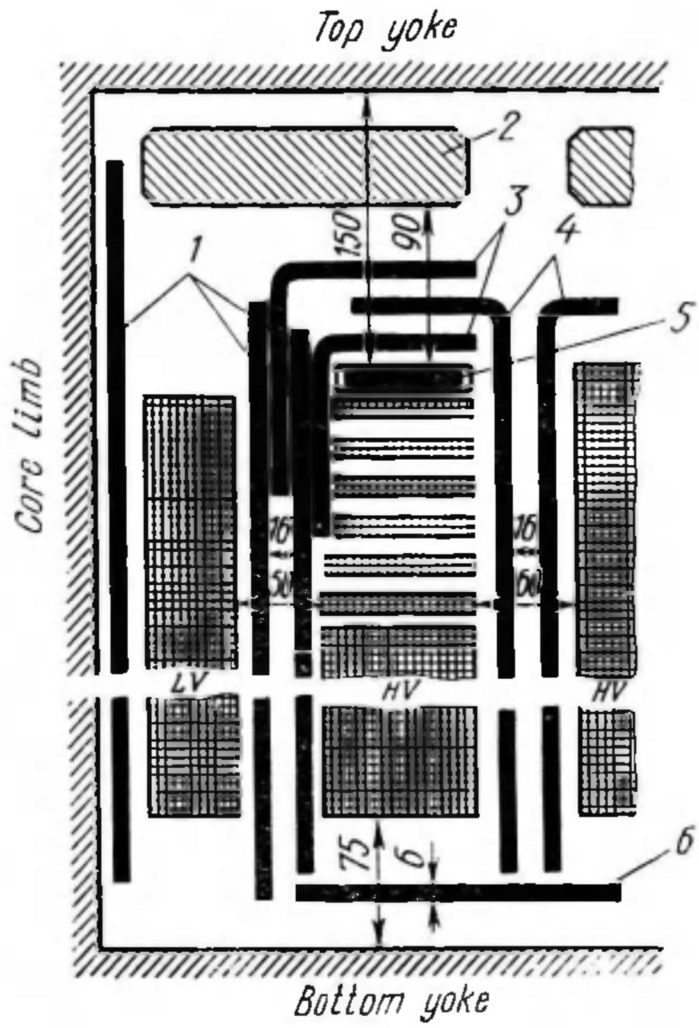


Fig. 3.46. Main components of the major insulation and the oil spaces in a 110-kV three-phase transformer with the line lead taken from the top end of the winding (the test voltage for the major insulation of the HV windings is 200 kV)

1—pressboard cylinders; *2*—steel pressure ring; *3*—pressboard collars; *4*—interphase insulation (barrier); *5*—capacitance-grading ring; *6*—bottom insulating barrier

The windings are insulated from the tank by oil spaces whose size depends on the voltage class of the transformer. For example, at voltages from 6 to 10 kV the distances from the windings to the tank walls must be at least 25 mm, while at 35 kV, 65 mm.

Minor Insulation. This includes the interturn, intercoil (or interdisk), and interlayer insulation and also, insulat-

ion between the elements of capacitive protection. The interturn insulation is formed by the insulation of the coil conductors themselves. The intercoil insulation is an oil duct formed between the adjacent coils by insulating spacer blocks. The height of this duct is taken to be from 3 to 6 mm at voltages up to 35 kV and from 5 to 8 mm at 110 kV.

In double-layer windings, the insulation clearance between the layers is determined by the width of the oil duct between them, usually amounting to 5 mm. The interlayer insulation of the multiple-layer coils used in Size I and II transformers consists of several layers of cable paper. There may be from 2 to 5 layers of 0.12 mm thick paper, depending on the total number of the coil layers. To obtain the essential interlayer creepage at the coil ends, the interlayer insulation is made to project 12 mm beyond the coil layers.

Insulation of Tap-Changing Arrangements and Leads. This includes the oil spaces and solid-insulation components that insulate the tap-changing arrangements and leads from the tank and other earthed parts of the transformer. According to the standards specifying the minimum creepage distances for oil, pressboard, wood, and other insulating materials used in transformers of various classes, the oil spaces between the tank walls and leads with a one-side insulation thickness of 2 mm should be at least 10 mm at voltages from 6 to 10 kV and 40 mm at 35 kV; at a voltage of 110 kV and a one-side lead-insulation thickness of 20 mm, the oil spaces should be from 75 to 90 mm.

The necessary insulation clearances between the live and earthed parts depend on the shape of these parts: for angular parts they are greater than for smooth and flat parts.

In dry-type transformers, insulation clearances are substantially greater, because the electric strength of air is much inferior to that of transformer oil.

External Insulation

The external insulation comprises the air spaces between the live parts of the terminal bushings and between the bushings and earthed parts of the transformer. Insulation clearances are selected in accordance with the standard creepage distances for air. Here are some of them:

Voltage, kV	Minimum distances between bushings, mm
6	80
10	110
35	300
110	840

The insulation clearances between the bushings and earthed parts (explosion vent, oil conservator, etc.) are taken at nearly the same values. In practice, these clearances are increased by 10 to 15 mm to allow for possible size deviations in transformer assembly.

3.9. Transformer Tank, Coolers, Oil Conservator, Thermosiphon Filter, and Other Transformer Fittings

In operation, the heat given off by the core, windings, and other current-carrying parts of the transformer is transferred to the oil which surrounds them. The oil transfers the heat by conduction and convection to the walls of the transformer tank whose external surface dissipates it into the surroundings. Such a method of heat removal is called oil-natural cooling.

As the capacity of the transformer grows higher, the absolute power loss in it increases and consequently, the amount of heat that the tank walls must dissipate. With natural oil circulation, each square metre of the tank surface can dissipate from 400 to 450 watts of power. If the incoming heat load on the tank surface should be greater, the temperature of the core-coil assembly and the transformer as a whole would rise prohibitively high, this impairing its reliability.

In low-capacity transformers (25 to 40 kV A), the absolute loss of power dissipated as heat is comparatively low, so they use plain tanks. The cooling surface of larger units has to be increased by welding steel tubes on to the tank walls or by fitting the tank with detachable tubular coolers (radiators). Where such radiators cannot provide for adequate heat removal, a blast of air is forced onto them by means of special propeller-type fans. This method of heat removal

is called oil-natural air-blast cooling. Transformers of very large sizes use combination cooling systems, such as forced-oil air-blast and forced-oil and water.

The Tank

The transformer tank is an oval or rectangular container intended for housing the core-coil assembly of the transformer. It is arc-welded from steel sheets, all the welds being of the oil-tight type. After manufacture, the tank is tested for tightness under a pressure of 0.5×10^5 Pa (gauge). At the top of the tank, there is a frame with bolt holes for fastening the tank cover. The cover closes the tank and serves as a support for mounting the oil conservator, terminal bushings, tap-changer drive, lifting lugs, etc. To facilitate moving the transformer, the tank is provided with a truck or undercarriages on rollers.

In major repair work, the cover has to be removed and the core-coil assembly withdrawn from the tank. The lifting of the core-coil assembly of high-capacity transformers requires heavy hoisting equipment, so the tanks of such transformers are made with a detachable bottom in order to ease the uncovering of the core-coil assembly. In this case, instead of unbolting the cover and lifting the core-coil assembly, they unbolt the bottom and lift the tank, leaving the core-coil assembly on its support—the tank bottom, the oil being preliminarily drained from the tank.

Transformers of up to 40 kV A generally have their terminal bushings mounted on the side walls of the tank, which also carry an oil gauge, transformer nameplate, lifting hooks, spark-gap protector bracket, oil-drain plug, and earthing bolt. The tank cover accommodates an oil-filler plug provided with an air-bleed hole, protective hood for the operating knob of the tap-changer, and thermometer pocket.

Transformers from 63 to 1 600 kV A in capacity are equipped with tubular tanks. The tubes on the tank walls may be arranged in one, two, or three rows, depending on the transformer capacity. At present, the transformer manufacturers in this country are putting out transformers equipped with elliptical tubes which, as compared with round tubes, provide for higher heat removal efficiency and can be placed

closer to one another along the tank periphery, so that more tubes can be accommodated on a given tank.

Figure 3.47 shows the Type TM-630/10 transformer whose cooling surface is increased by banks *2* of elliptical tubes. The tank is filled with oil through a globe valve *1* which also serves for draining the oil from the tank. Oil samples

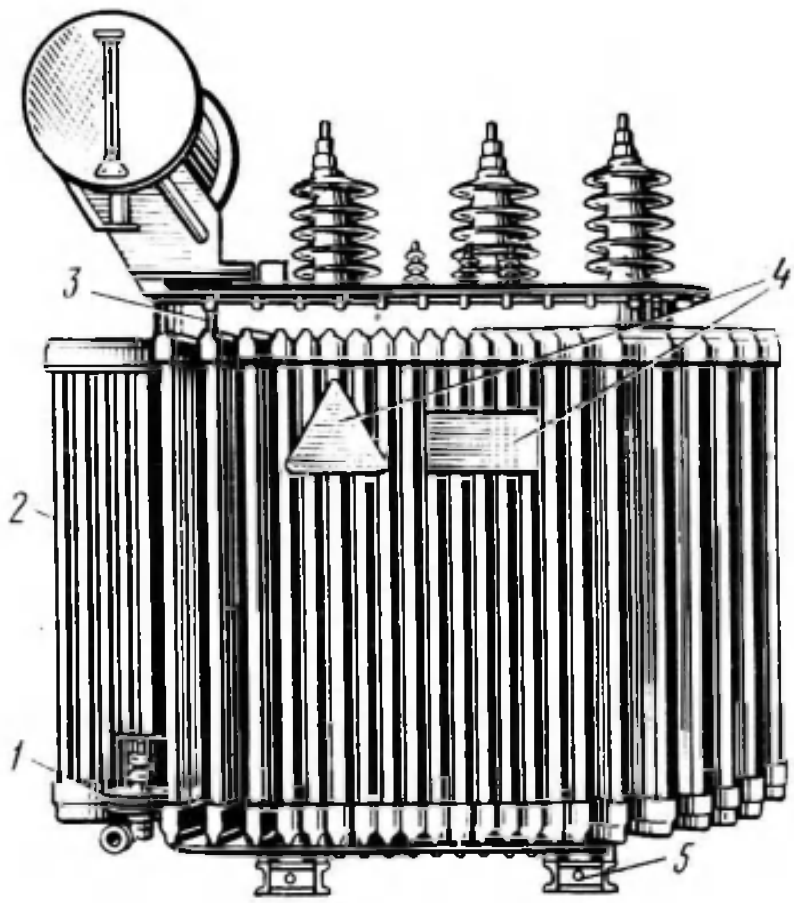


Fig. 3.47. Type TM-630/10 transformer

can be taken through a sampler mounted on the tank wall. In the tank bottom there is a hole normally closed by a sealed-off plug (not shown in the figure) which serves for draining oil residue from the tank during repair.

The tank has four hooks *3* for lifting the transformer and a truck on four rollers *5* for moving it horizontally. The tank cover is provided with special openings and studs for mounting and fastening the terminal bushings, tap-changer drive, valve, thermometer pocket, and pipe for connecting the tank to the oil conservator. Plates *4* welded on to the tube banks serve for mounting the transformer nameplate and temperature indicator.

Figure 3.48 shows the arrangement of the terminal bushings and other transformer fittings on a transformer cover,

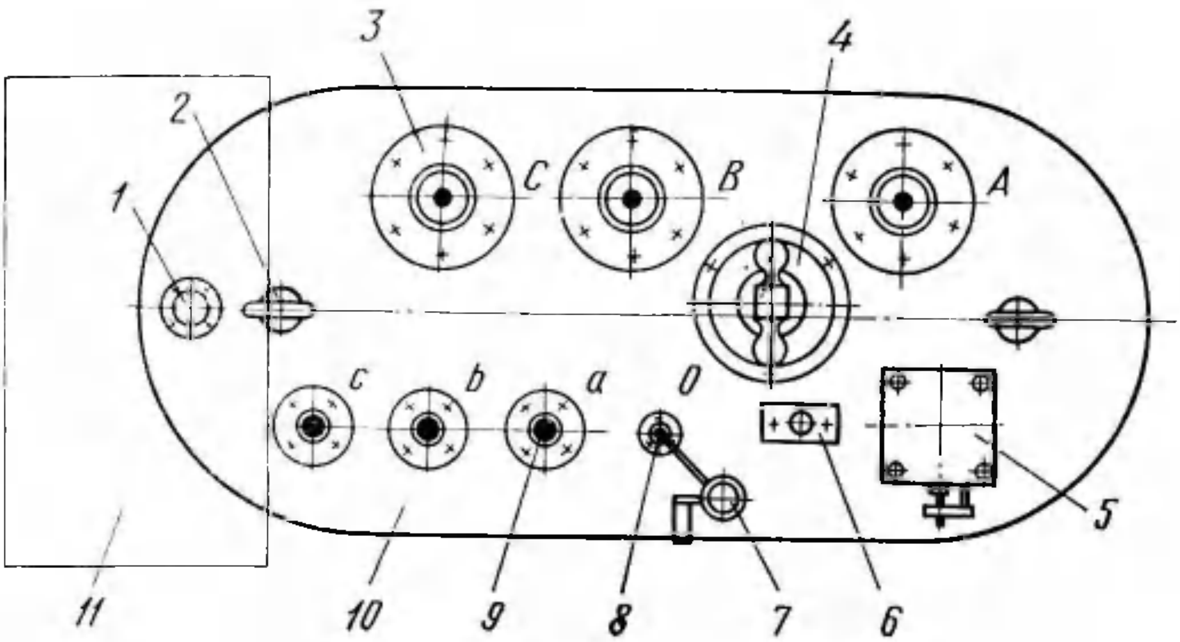


Fig. 3.48. Tank cover of the Type TM-400/10 transformer (plan view)

1—hole for connecting the tank to the oil conservator; *2*—eye-bolt; *3*—HV terminal bushing; *4*—tap-changer; *5*—valve; *6*—thermometer; *7*—spark-gap protector; *8*—LV neutral terminal bushing; *9*—LV line terminal bushing; *10*—tank cover; *11*—oil conservator site

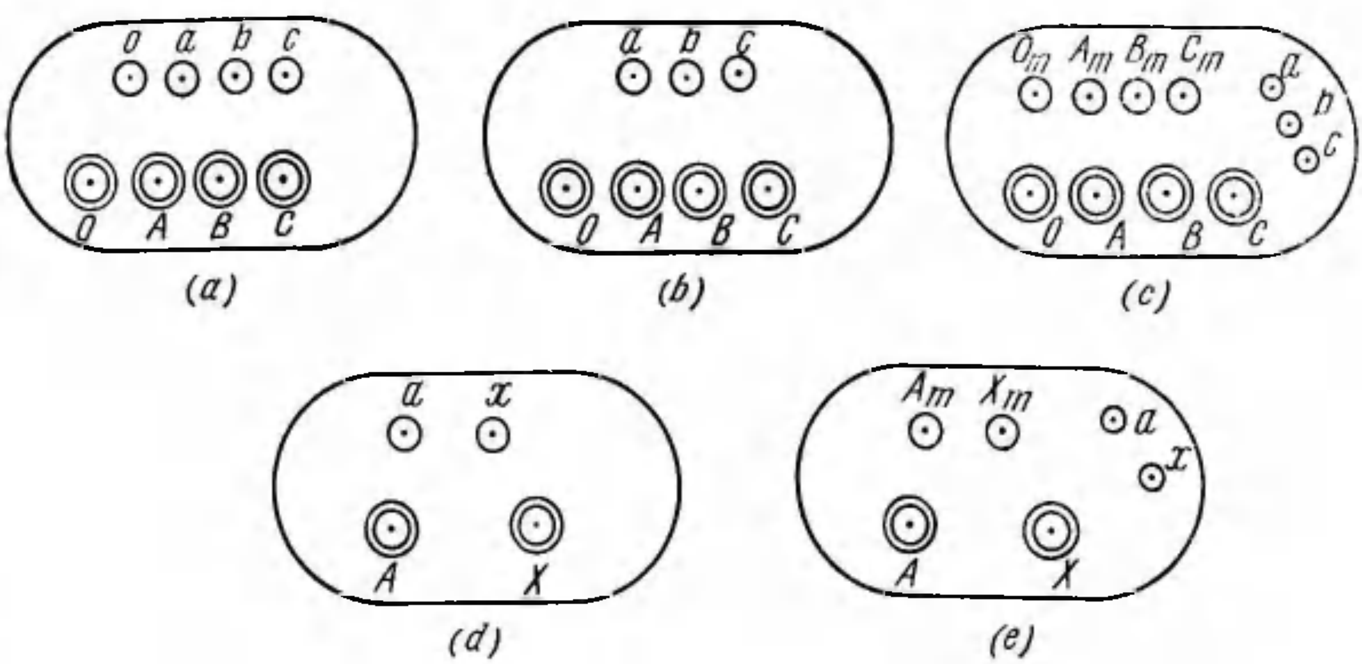


Fig. 3.49. Arrangement of terminal bushings on the tank covers of power transformers

(*a*) three-phase, two-winding transformers with the neutral points on the HV and LV sides being brought out; (*b*) three-phase, two-winding transformers with the neutral points on the HV side being brought out; (*c*) three-phase, three-winding transformers with the neutral points on the HV and MV sides being brought out; (*d*) single-phase, two-winding transformers; (*e*) single-phase, three-winding transformers

and Figure 3.49 illustrates the standard arrangement patterns for the bushings of various power transformers of Soviet make.

Coolers

Transformers larger than 1 600 kV A use detachable tubular radiators, so their tanks are reinforced by stiffening ribs and are provided with flanged ports for attaching the

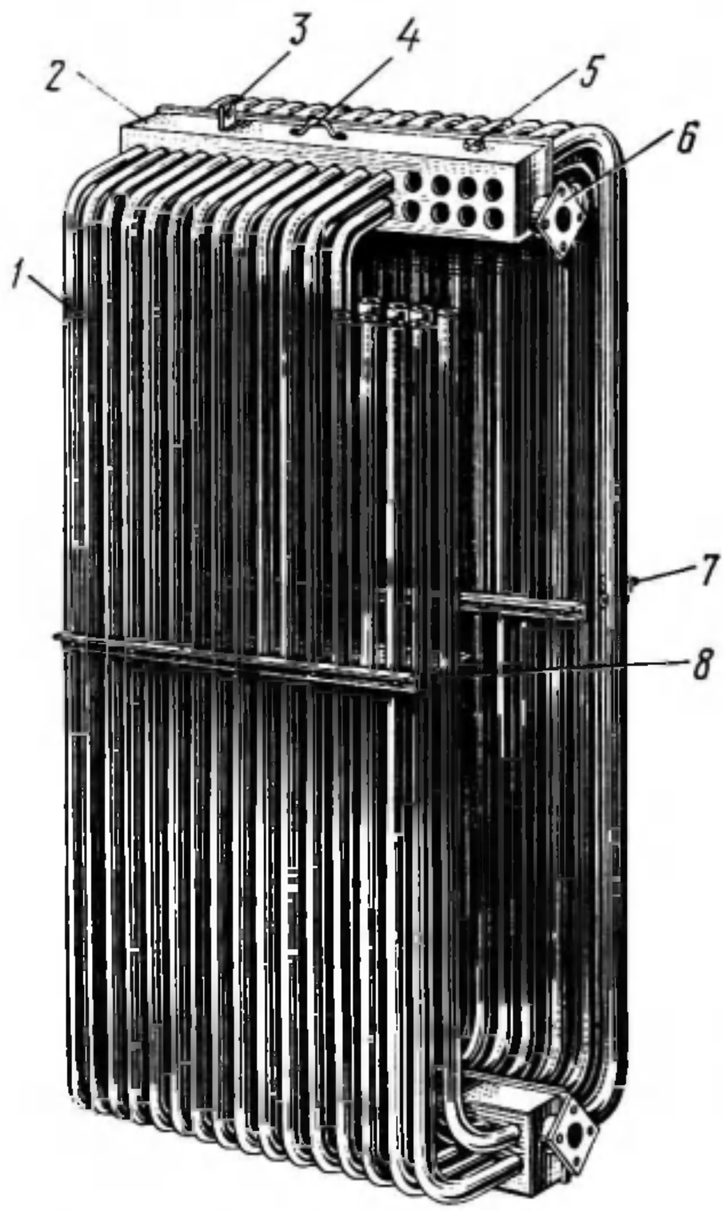


Fig. 3.50. Tubular radiator

radiators and radiator valves. The radiators and valves are flange-mounted and are fixed in place by means of special steel bolts.

A radiator (Fig. 3.50) consists of two rows of parallel tubes *1*, top and bottom headers *2*, and flanged ports *6* which

are welded into the ends of the headers and serve for mounting the radiator on the tank. Each header carries a lifting lug *4*, bracket *3* with a hole for mechanical connection of separate radiator banks, and plug *5*. The bottom header plug serves for draining oil from the radiator, while the top one is used for bleeding air from the radiator when the transformer tank is being filled with oil. To give them rigidity, the tubes in the parallel rows are joined by means of angle bars *7* and tubes *8* held together by bolts.

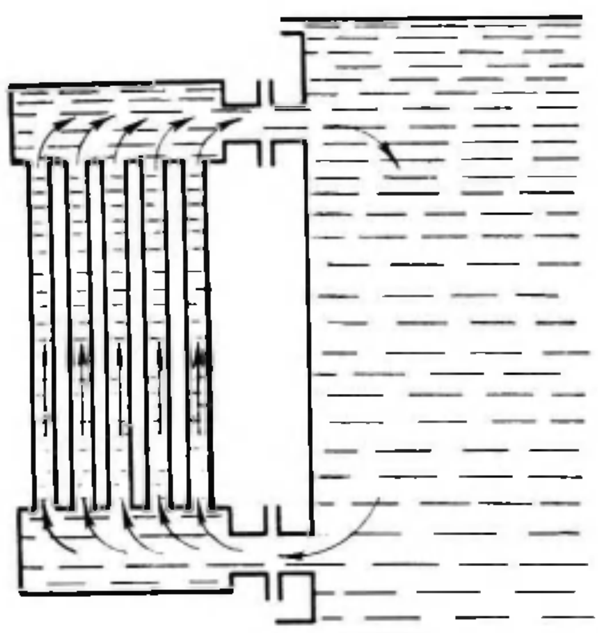


Fig. 3.51. Diagram of oil circulation in a radiator

The greater the surface of the radiator, the greater the amount of heat it can remove from the transformer. Single-sided tubular radiators are sufficient for units of 630 to 4 000 kV A. In such radiators, the tubes are arranged only on one side of the headers, and the flanged connecting ports are provided on the opposite side of the headers.

Lately, radiators with straight vertical tubes have been widely adopted. These use round or elliptical tubes of smaller diameter and wall thickness than single- or double-row tubular radiators of ordinary design. With several rows of comparatively closely spaced tubes, the straight-tube radiators are lighter and more compact. Also, their heat removal efficiency is higher and they are more easy to assemble and repair, since the tubes are straight and have the same length. Straight-tube radiators are attached to the transformer tank in the same way as the double-row tubular radiators of ordinary design; in small transformers, the attachment is without flanged connections, the connecting pipes being welded directly into the tank walls.

In operation, hot oil rises to the top of the tank and enters the top radiator header (see Fig. 3.51). The large cooling surface of the radiator causes the temperature of the oil to drop. Since there is a difference in density between hot and

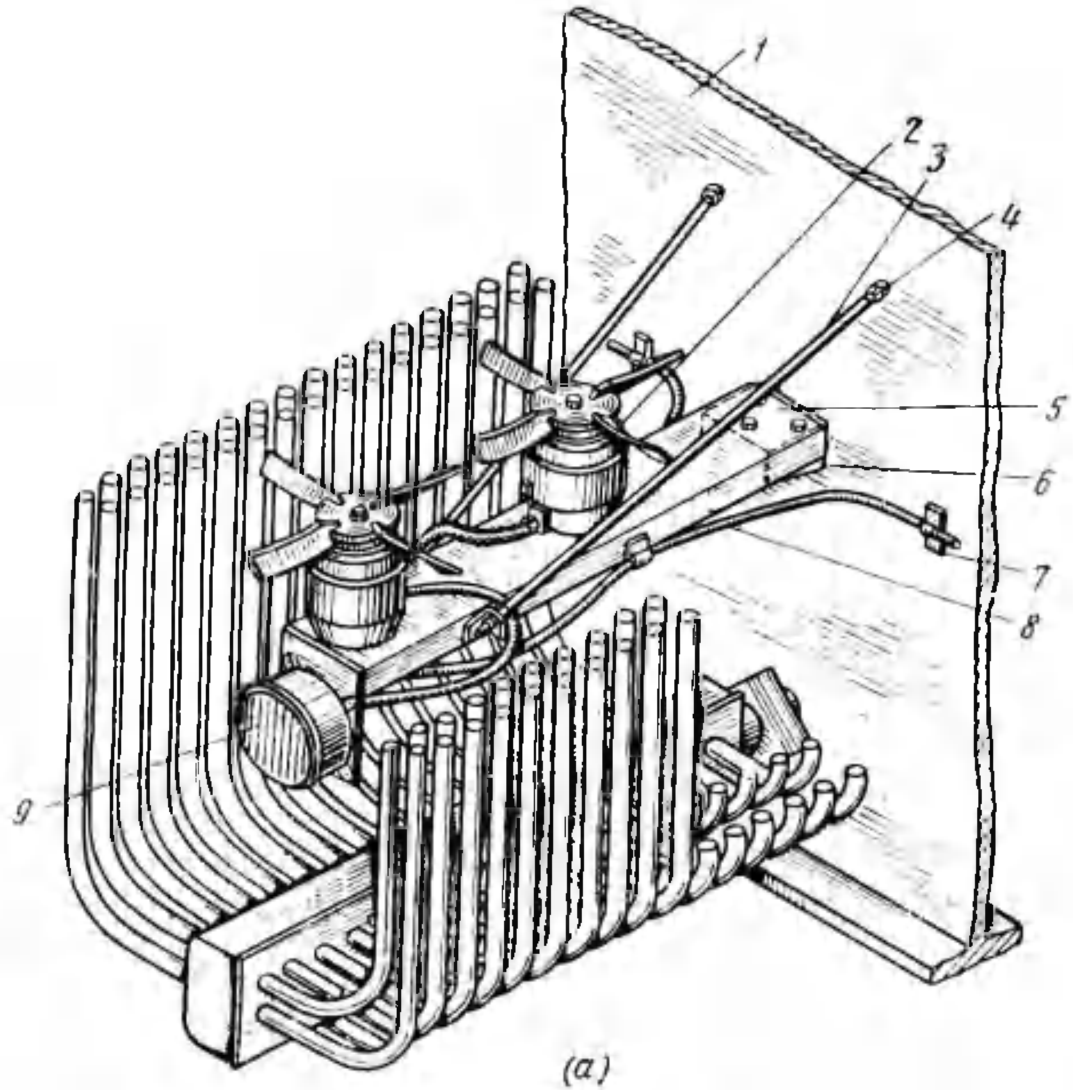
cold oil, the oil, while cooling, descends down the radiator tubes, giving away its heat to the tube walls that dissipate it into the ambient air. Fresh portions of hot oil from the tank enter the top radiator header, replacing the cooled oil which flows into the tank from the bottom header. In this way, natural oil circulation sets in in the transformer.

In high-capacity transformers, where the surface of the radiators with natural oil circulation cannot dissipate enough heat, resort is made to forced-air cooling. As a rule, two fans are used to force an air blast onto each radiator. The fans are mounted on a special bracket *5* (see Fig. 3.52*a*) designed to reduce vibrations. The bracket is held to the tank wall *1*. The forced air materially increases the removal of heat from the radiator surface, bringing it up to 750 or even 800 watts per square metre over against 450 to 500 W/m^2 attainable with oil-natural cooling. This cooling system is called oil-natural air-blast and is designated by the letter Д.

Transformers and autotransformers of 90 000 kV A and upwards employ combination forced-oil air-blast coolers, because oil-natural air-blast cooling systems do not provide for adequate heat removal here. Such cooling systems are designated ДЦ. A cooler of the ДЦ system (Fig. 3.52*b*) is a compact motor-car type radiator *12* consisting of several rows of finned aluminium tubes welded into the top and bottom tube plates. The fins on the tubes are obtained by knurling. At the top and bottom of the radiator there are oil chambers or headers *11*. An electric circulating pump *10* is connected to the top radiator pipe, and a flap-and-nozzle relay *15* which controls the oil circulation through the radiator is attached to the bottom radiator pipe.

The pump sucks the hot oil from the top portion of the transformer tank and forces it through the radiator and into the bottom portion of the tank. In the radiator, the oil is cooled by the forced air blast provided by two fans *13* equipped with diffusers *14* which are installed one above the other and direct the air blast onto the radiator. The fans are mounted on brackets which are either fastened to the radiator itself or installed near it.

High-capacity transformers are most effectively cooled by what is known as forced-oil and water systems designated by the letter Ц. In these systems, the hot oil from the top



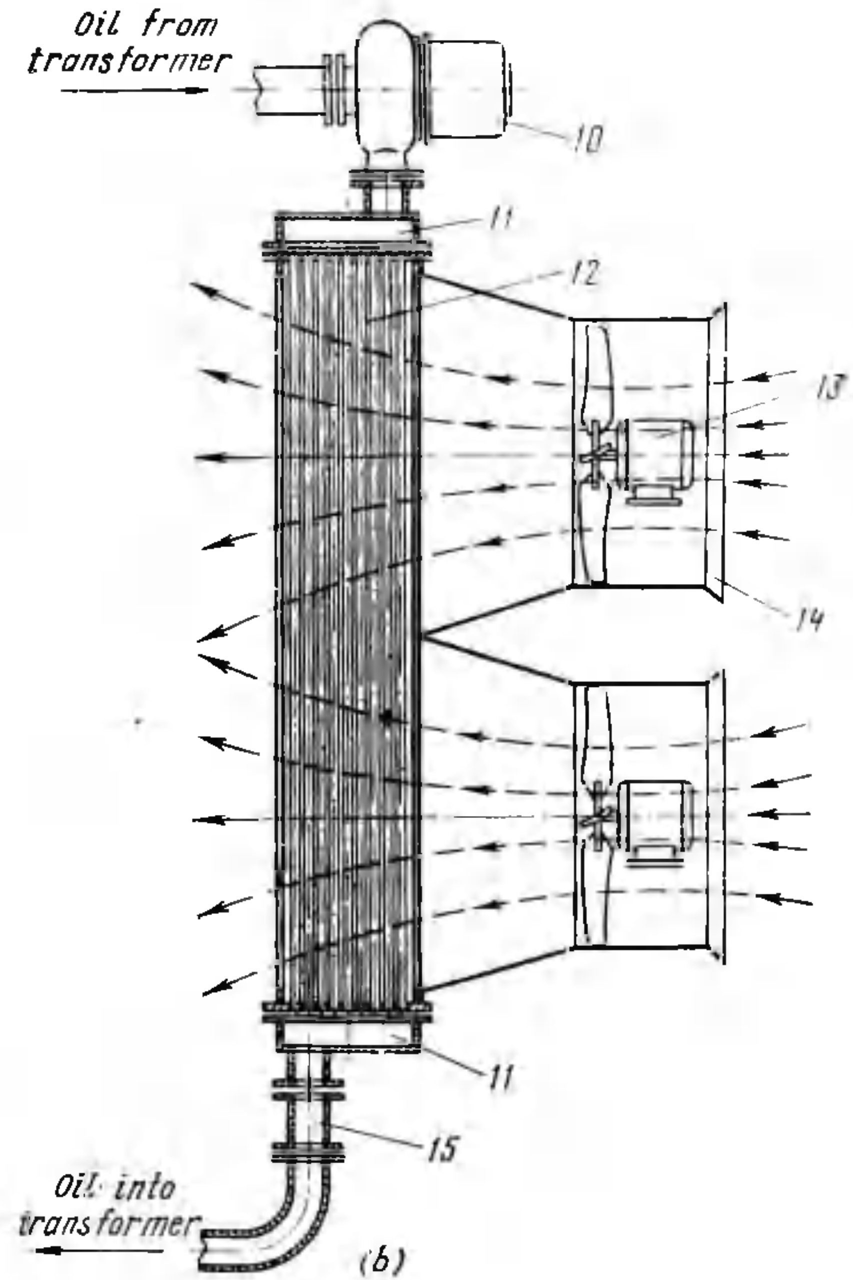


Fig. 3.52. Coolers

(a) Д system; (b) ДЦ system; 1—tank wall; 2—motor; 3—brace; 4—boss; 5—bracket; 6—angle; 7—cable fastening; 8—three-core rubber cable in a flexible conduit of galvanized steel ribbon; 9—distribution box; 10—electric pump; 11—oil chambers (headers); 12—motor-car type radiator; 13—fan; 14—diffuser; 15—flap-and-nozzle relay

portion of the transformer tank is forced by a circulating pump through an external countercurrent pipe heat exchanger and into the bottom portion of the tank. The inlet and outlet ports in the tank and heat exchanger are arranged diagonally.

In the heat exchanger, the oil is cooled by water which is forced through the cooling pipes of the exchanger. The

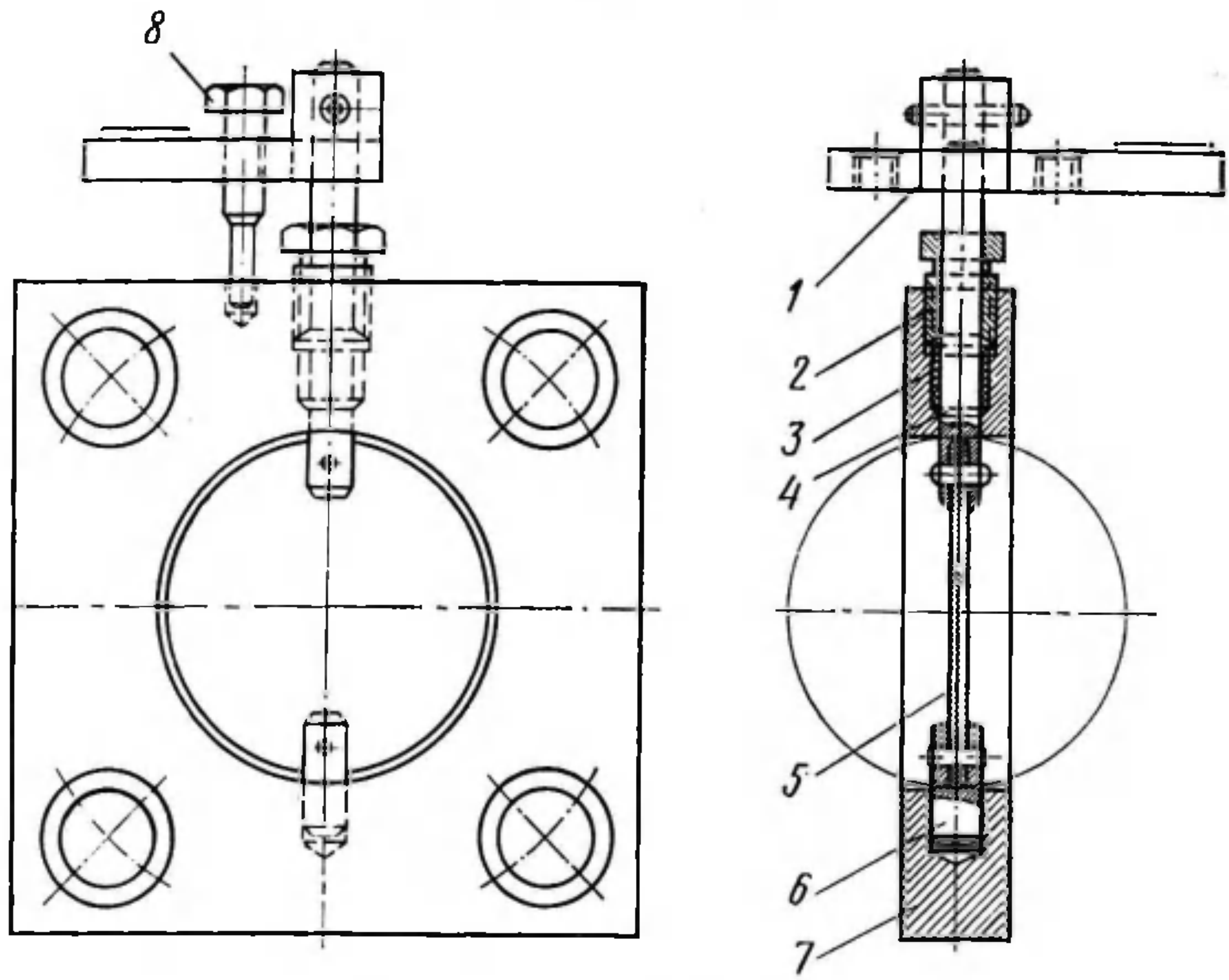


Fig. 3.53. Radiator valve

hot oil enters the interpipe space of the heat exchanger at its bottom and leaves it at the top, while the cooling water flows through the pipes in the opposite direction, i.e., from the top of the heat exchanger downwards.

Where detachable radiators or other cooling arrangements external to the transformer are used, the flanged connections between the tank and coolers incorporate flat radiator valves (Fig. 3.53). These enable faulty radiators to be replaced without draining oil from the tank, which is of great importance for repairs. The valve consists mainly of a rectangular steel or cast-iron body 7 and a rotary disk (shut-off valve) 5 which

fits the bore of the valve body where it pivots on fulcrum pins *4* and *6*. The pin *4* projects outside through a sealing gland *3* with a gland nut *2*. The outer end of this pin carries a control handle *1* which serves to close or open the valve by turning the disk, thereby breaking or establishing communication between the tank and radiator. The sealing gland prevents oil leakage along the pin *4*. The disk can be locked in the closed or open position by means of a stop bolt *8*.

Radiator valves cannot provide for hermetic sealing between their disks and bores, therefore, to prevent oil leakage from the tank, blind flanges with rubber sealing gaskets are installed on the valves whenever the radiators are removed for any prolonged period of time.

Oil Conservator

As the load on the transformer and the temperature of its surroundings vary, the temperature of the oil filling the transformer also changes. Under the same load conditions, the temperature of the transformer oil is higher in summer than in winter. Temperature variations cause changes in the oil volume in the transformer tank. To ensure that the tank is always completely filled with oil, transformers having a capacity from 25 kV A upwards and working at 6 kV and over use a special expansion tank called oil conservator.

The conservator is a metal vessel, usually cylindrical, which communicates with the main transformer tank. Figure 3.54 shows the oil conservator of a Size III transformer. It is installed slightly above the level of the tank cover *6*. As the oil gains in temperature, it is forced out of the tank and into the conservator via a pipe connecting the tank to the flanged connection *5* of the conservator; when its temperature falls, the oil flows back into the tank. The conservator tank is mounted on the main tank cover on brackets *10* and support plates *9*.

The conservator reduces the oil surface exposed to air, thus lowering the rate of sludging and acid-production. Its capacity must be such as to ensure that it is never empty of oil, irrespective of any normal variations in the trans-

former operating conditions (from off-circuit to full load) and ambient temperature (from —45°C to +40°C), the volume of oil in the conservator amounting to 8 or 10% of that in the main transformer tank.

One of the end walls of the conservator accommodates an oil level gauge *1* whose glass bears three painted horizontal lines, marked —45°C, +15°C, and +40°C, which fix the oil level in the inoperative transformer corresponding

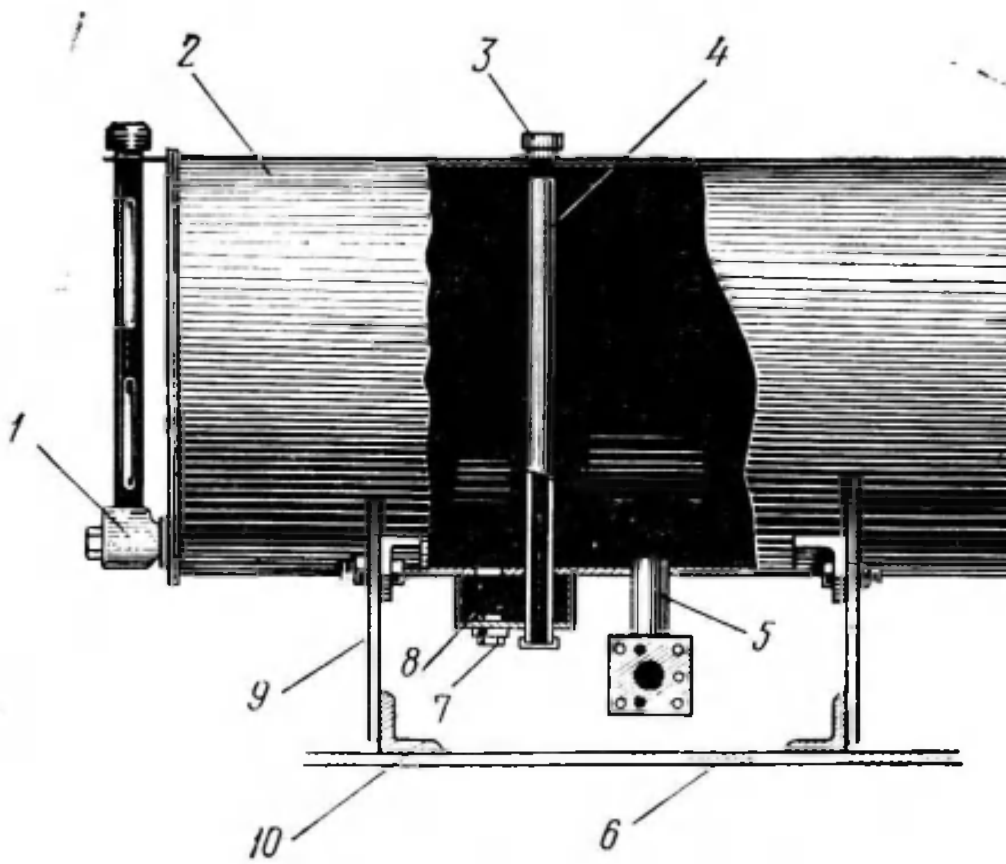


Fig. 3.54. Oil conservator

to the indicated ambient temperatures. The opposite end wall of the conservator is made detachable to facilitate cleaning and painting the conservator on the inside during repair.

The oil gauge serves for checking the oil level in the transformer both when filling it with oil at the factory and in service. It operates on the principle of communicating vessels, but to prevent the ingress of atmospheric moisture and impurities, its upper part is made to communicate with the air-filled space above the oil in the conservator, rather than directly with the atmosphere.

A simple oil gauge of this type is shown in Fig. 3.55. It is used in Size III through VII transformers. The glass *7* is a thick-walled tube, so there is no need in any protective

metal shroud. The tube is held in two metal elbows where it is sealed by means of rubber O-rings pressed against the glass and the inner surfaces of the sockets by glands *5* and *8*.

Figure 3.56 shows a flush fitting of the glass window pattern which is used in Size I and II transformers. This type

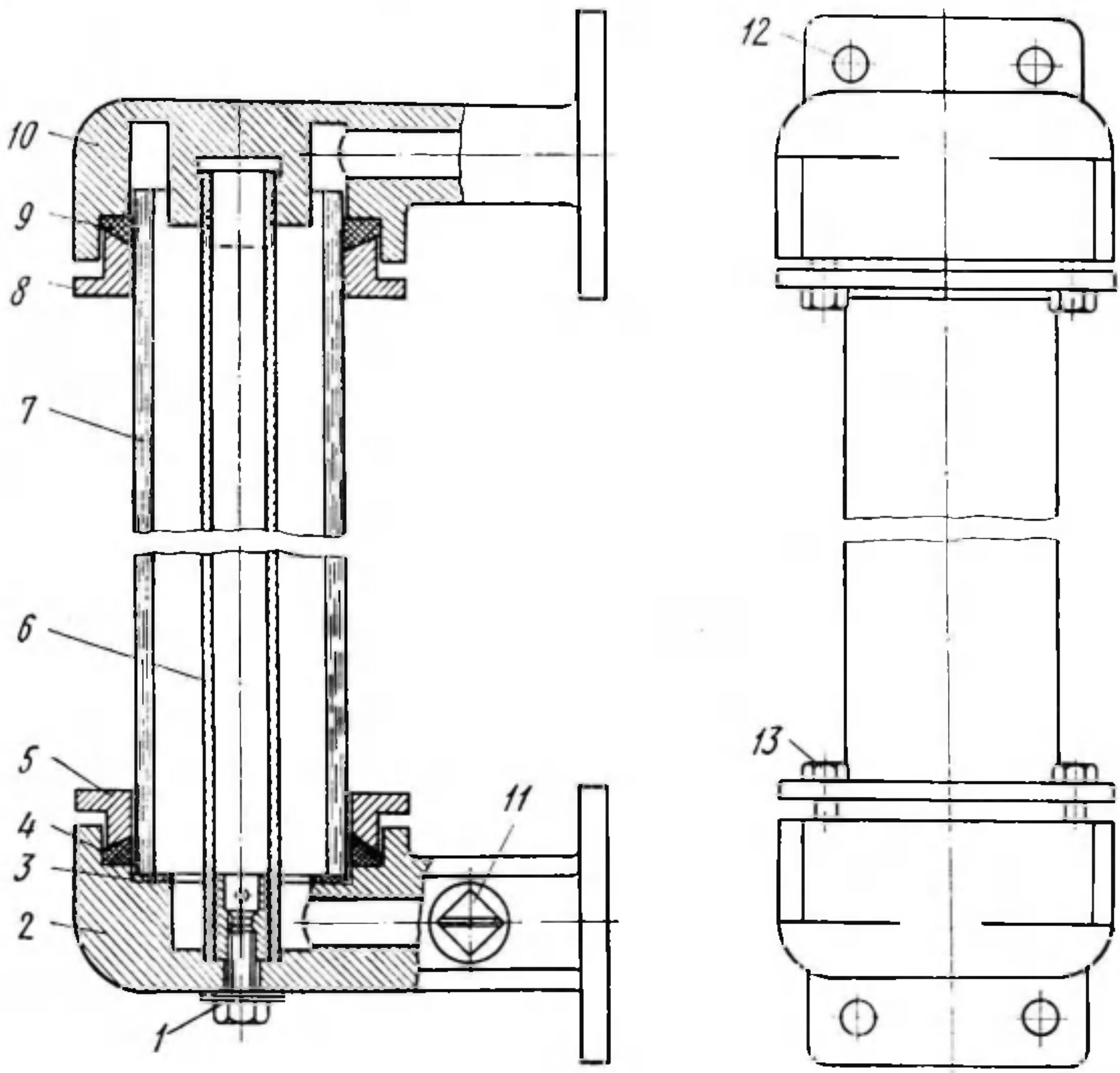


Fig. 3.55. Oil gauge of Size III through VII transformers

1—bolt for mounting the tube *6*; *2*—bottom elbow; *3*—annular pressboard gasket; *4* and *9*—rubber O-rings; *5* and *8*—glands; *6*—steel tube; *7*—thick-walled glass tube; *10*—top elbow; *11*—plug valve; *12*—mounting hole; *13*—gland-fixing bolt

of oil gauge is arranged as follows. A vertical slot *1* 10 mm wide is cut in the end wall of the conservator. A rubber gasket *3* is placed around the periphery of the slot and a flat lass *2*,3 mm thick is put over the gasket so as to cover theg slot. Then the glass is pressed against the gasket by means

of a shaped metal flange (bezel) which is put over the glass and fastened to the conservator wall with nuts *6* screwed on studs *5* welded to the conservator.

In the case of large transformers, the conservators are a fair distance from the ground and so the oil level is difficult

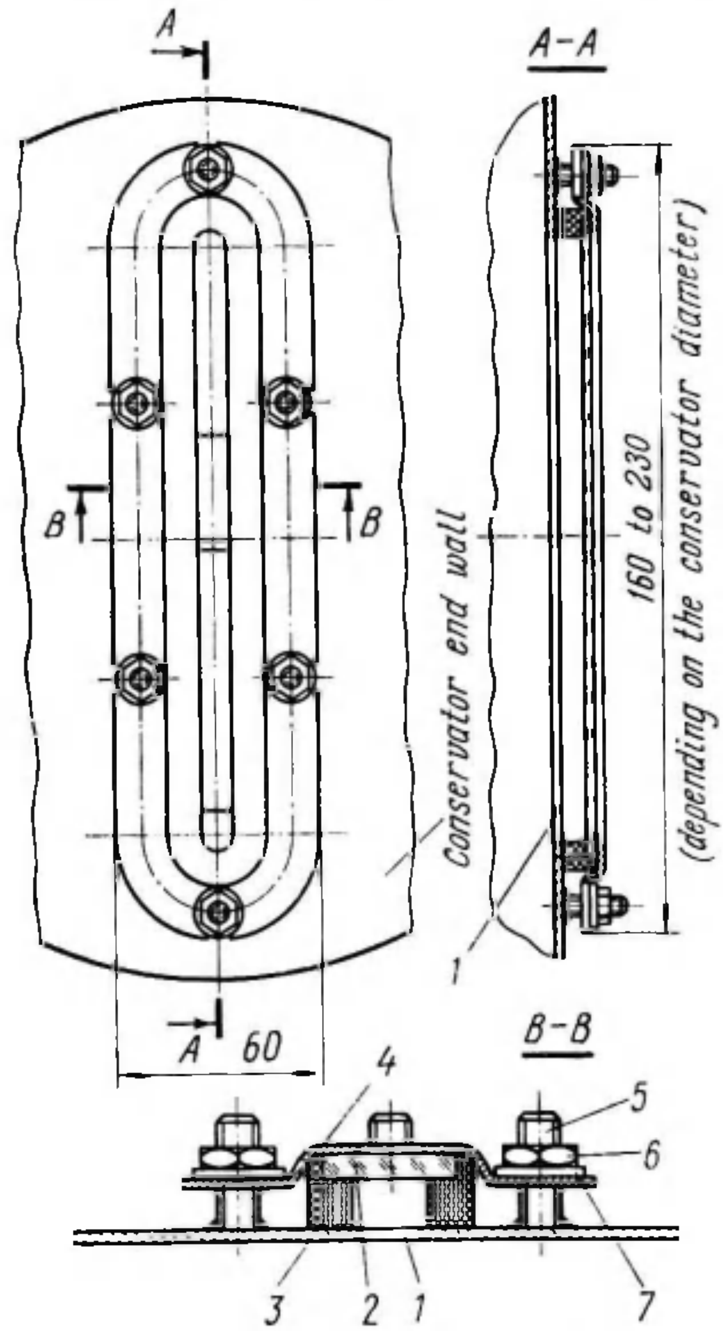


Fig. 3.56. Oil gauge of Size I and II transformers

1—vertical slot; *2*—flat glass; *3*—rubber sealing gasket; *4*—shaped flange (bezel); *5*—stud; *6*—nut; *7*—washer

to read. It is advisable, therefore, on such units to fit a level gauge of the dial pattern. A particularly suitable dial gauge is the magnetic type, since oil leakage cannot occur. In the near future all the newly manufactured transformers in this country will be equipped with oil gauges of this type.

Sludge and moisture accumulate at the bottom of the conservator, and to remove them, the conservators of transformers up to 400 kV A in capacity are provided with a drain plug. Larger units use a metal sump *8* (see Fig. 3.54) where

sludge, moisture and mechanical impurities are collected for eventual removal. The sump is welded to the conservator from beneath and has a drain plug *7*.

As the oil level in the conservator varies, so does the volume of the air above the oil: air is either drawn in the conservator from the atmosphere or is exhausted into it. Therefore, it is customary to say that the conservator "breathes". The conservator communicates with the atmosphere through a breather incorporating a dehydrator, which is connected to the breather pipe *4*. A plug *3* serves for filling the conservator with oil. To prevent any sludge and impurities from getting into the main tank, the end of the connection *5* projects 50 to 60 mm into the conservator.

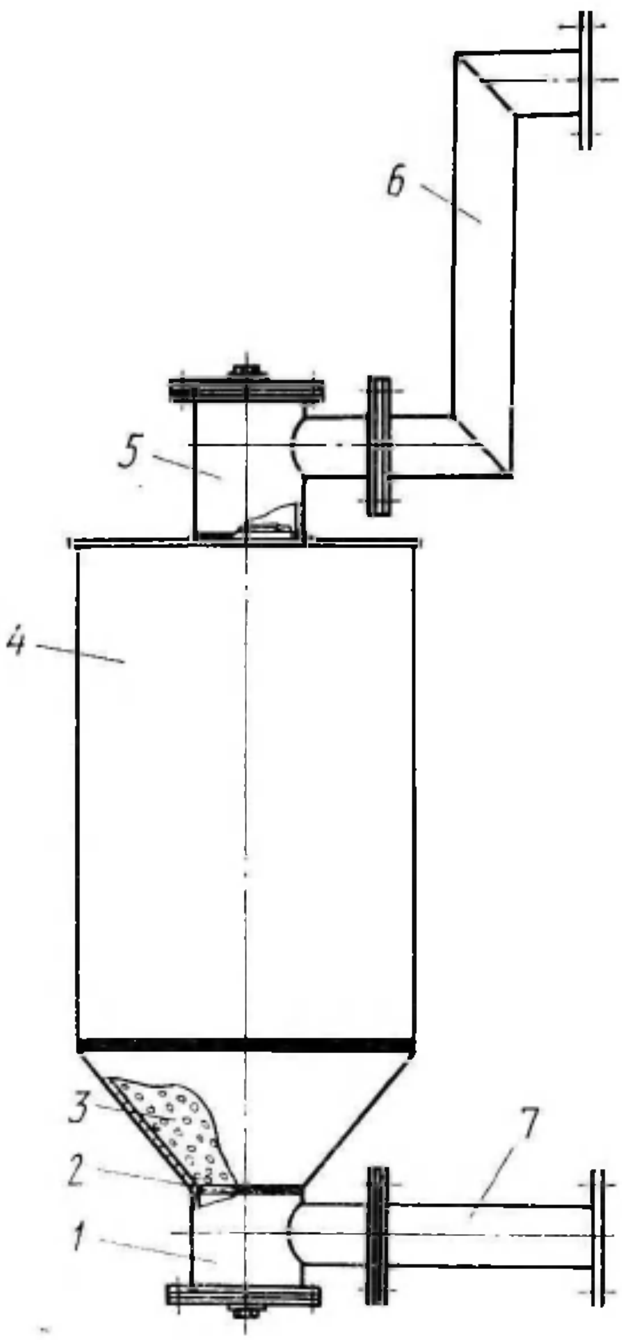


Fig. 3.57. Thermosiphon filter

Thermosiphon Filter

In operation, transformer oil is heated; it contacts with air and absorbs moisture from it. All this leads to eventual deterioration of the insulating properties of the oil—the oil ages. The ageing is caused mainly by the oxygen contained in the air, which oxidizes the hot oil. The oil grows dark and turbid, its viscosity increases. There appears sludge which accumulates on the windings and core and obstructs the oil ducts. The moisture content of the oil grows higher and acids are formed in it that destroy the transformer insulation.

To prevent oil deterioration, use is made of a device called a thermosiphon filter. This filter (Fig. 3.57) partially cleans

and regenerates the oil while the transformer is in operation. The thermosiphon filter is a metal cylinder *4* filled with silica gel *3*, which is connected by pipes *6* and *7* to the transformer tank in the same manner as a radiator. Chamber *5* at the top of the filter serves to fill it with silica gel, while the used silica gel is discharged through a chamber *1*. The chambers are equipped with screens *2* to prevent the ingress of silica gel into the tank. The oil circulates through the filter by thermosiphon action and, in the process, is continuously cleaned of sludge, acids and moisture and so can serve for years without special cleaning and regeneration. Thermosiphon filters are employed on transformers of 2 500 kV A and upwards.

Breather

This is a special air filter incorporating a dehydrating material (silica gel). It is used to prevent the ingress of moist, contaminated air into the conservator. Depending on the construction and size of the transformer, the breather (Fig. 3.58) is mounted either on the conservator or on the main tank. At present, the breathers of Size II and III transformers are built into the conservators.

The breather consists of a metal cylinder *1* filled with silica gel *3*, a wire-mesh screen *7*, and a perforated cartridge *4* filled with indicator silica gel and closed by a cover *5* equipped with a sight glass *6*.

At the bottom of the breather there is an oil seal operating on the principle of communicating vessels, which prevents the silica-gel dehydrator from being constantly in contact with the ambient air and thus continuously adsorbing moisture. The oil seal also serves to remove mechanical impurities from the air, which precipitate in the oil filling the seal when the air passes through it.

When the oil level in the conservator drops, fresh air is drawn into it through the breather. The air passes through the tube *9* welded to the bottom *12* of the oil seal, the transformer oil *11* filling the seal, holes in the oil seal wall *8*, the wire-mesh screen, and the silica-gel dehydrator which absorbs moisture from it. Then the cleaned, dry air enters the conservator by a pipe connected to the flanged connect-

ion *2* of the breather. When the oil volume in the conservator increases, the air flows in the opposite direction and is exhausted into the atmosphere.

The oil seal is provided with several plugs. A plug *14* serves for filling the seal with transformer oil, a plug *13*,

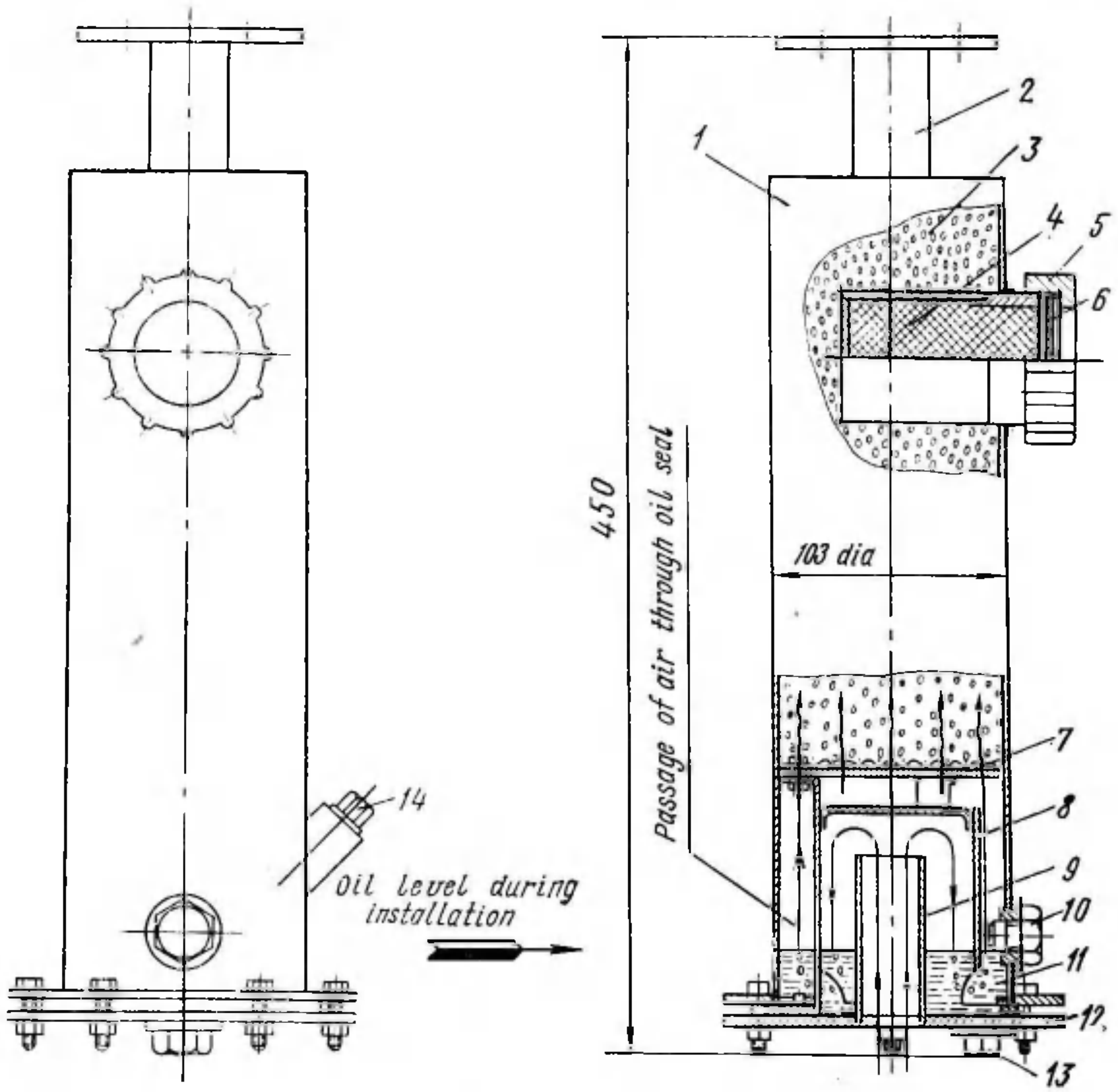


Fig. 3.58. Breather

for draining the used oil from the seal, and a plug *10*, for draining any excess oil that might raise the oil level in the seal above the normal (indicated by an arrow in the figure).

A visual check on the oil level in the seal is provided by an oil gauge (not shown in the figure).

The silica-gel dehydrator in the breather is periodically changed. An indication that the silica gel has become moist and requires replacement is the change of the colour of the

indicator silica gel from light blue to pink. The colour of the indicator silica gel is observed through the sight glass in the cover of the indicator cartridge.

The breather uses Grade KCM silica gel in grain sizes from 2.7 to 7 mm, impregnated with a calcium chloride solution. The indicator silica gel is additionally impregnated with a cobaltic chloride solution. Silica gel is dried at a temperature from 100 to 120°C prior to charging the breather with it.

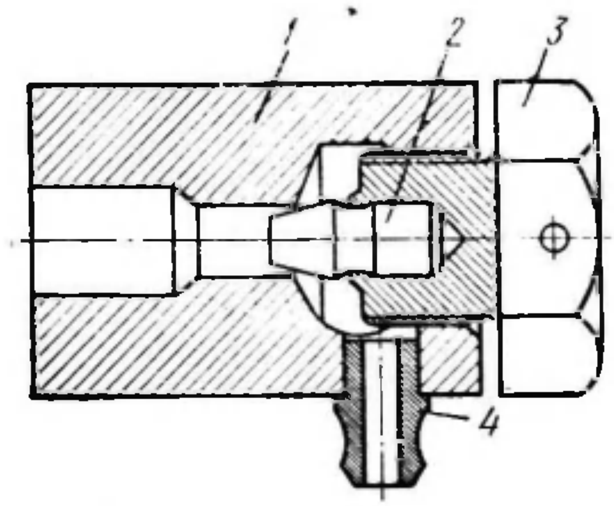


Fig. 3.59. Oil sampler

Oil Sampler

Samples of transformer oil for tests are taken from the tank through a special device (Fig. 3.59) mounted on the tank wall at the lower part of the transformer. It consists of a steel body *1*, a stopper *2* which is free to turn in its seat in a plug *3*, and a nipple *4*. As the threaded plug is screwed out of the body, the oil in the tank forces the stopper to the right and flows out through the nipple.

3.10. Protective Devices and Instruments

Explosion Vent

Failures inside the transformer are frequently accompanied by arcing. The high temperature of electric arc causes intensive decomposition of transformer oil, the gas evolved in the process greatly increasing the pressure inside the tank. In the event of a short circuit the pressure inside the tank grows so high that the tank may explode and cause an outbreak of fire.

To avoid damage to the transformer tank, an explosion vent (Fig. 3.60) is provided. It consists of a knee-shaped tube *2* made of sheet steel 1.5 mm thick, whose top end is closed by a diaphragm *4* with a flat, round glass. The lower end of the tube communicates with the tank through an opening

in the tank cover. Should the pressure inside the tank grow too high, the glass will break and the gas, together with oil, will be expelled from the tank through the tube.

The explosion vent tube at its lower end is provided with a flange *1* for bolting the tube to the tank cover, and there are two flanges, *9* and *11*, at the top end of the tube for mounting the glass disk *12* sealed by rubber gaskets 7 and *8*. A ring *10* welded to the flange *9* serves for centring the gaskets. An oil-tight weld is used on the joint between the flange *9* and the tube wall *6*.

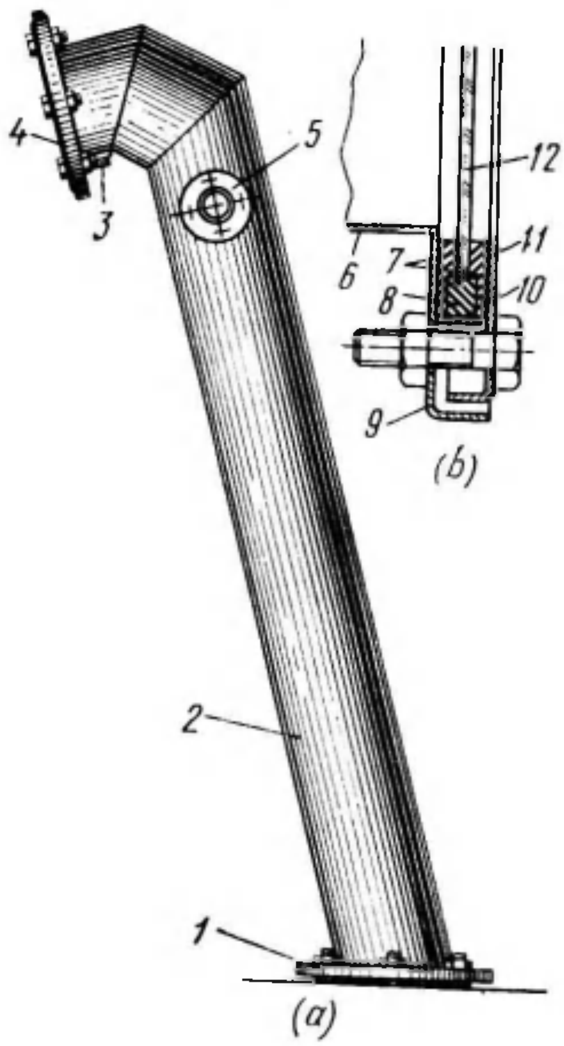


Fig. 3.60. Explosion vent

(*a*) external view; (*b*) mounting of the glass in the diaphragm

Formerly, explosion-vent tubes were equipped with a holed plug (at *3* in Fig. 3.60) to bleed air from the tube when filling the transformer tank with oil and to permit of the ingress and egress of air in accordance with temperature variations in the tank, but nowadays, to prevent any other contact of the oil with air except in the conservator, the tube is connected to the air space of the conservator by means of a small-gauge steel pipe bolted to flange *5* on the tube. Where such plugs are still in use, they must be stopped altogether and connecting pipes fitted between the explosion-vent tubes and conservators. Explosion vents are used on transformers of 1 000 kV A and over.

Buchholz Relay

Any fault which occurs inside the transformer is generally accompanied by the evolution of gas due to the decomposition of insulating materials (oil, paper, pressboard, wood, etc.) under the influence of elevated temperature. With minor faults, the gas evolution is slow, the gas bubbles gradually rise to the tank cover and then enter the conservator through

the oil pipe connecting the tank to the conservator. In the case of grave faults, oil rapidly flows through the pipe and is expelled into the conservator under the pressure of a large amount of gas evolved.

The Buchholz relay is a gas-operated device connected between the transformer tank and the conservator. It is fitted with alarm and tripping contacts, so that warning can be given of incipient gas evolution and a major breakdown can be averted. On its way from the tank to the conservator, the gas is collected in the relay housing, and after the gas collected has reached a preset volume, the relay gives an audible or visible warning of the fault. When there is an intensive flow of oil from the tank into the conservator, the relay trips the circuit breaker of the transformer. Besides fault indication, this relay will also indicate oil leakage should the conservator and pipe become empty of oil.

An analysis of a gas sample taken from the Buchholz relay of a faulty transformer helps to determine the nature of the fault. Usually, under normal conditions, the gas dissolved in the transformer oil has the following composition: 70 to 79% nitrogen, 20 to 30% oxygen, and 0.1 to 0.2% methane; hydrogen and acetylene are absent. A sharp change in the gas composition (for example, 50 to 70% hydrogen, 3 to 10% methane, 10 to 25% acetylene, 4 to 8% oxygen) testifies to a grave internal fault accompanied by arcing (insulation puncture, shorted turns, flashover in the contact system of the tap-changer, etc.). In the event of minor faults not accompanied by violent oil decomposition and gas evolution, the gas composition may be as follows: 2 to 5% hydrogen, 0.5 to 1% methane, 0.5 to 2% acetylene, 85 to 92% nitrogen and 5 to 8% oxygen. Such a gas composition bears witness to a fault, such as shorted parallel conductors in the windings, poor contacts in the tap connections or soldered joints, or closed paths in the magnetic system of the core, which, if not remedied, may eventually lead to a serious trouble.

Soviet-made transformers use two types of Buchholz relay, namely, the ПГ-22 float-type relay and the РГЧЗ-66 cup-type relay.

Figure 3.61a shows the ПГ-22 float-type Buchholz relay. The cast-iron housing *1* of the relay accommodates two metal floats, *3* and *5*, which are free to turn about their pivots. The

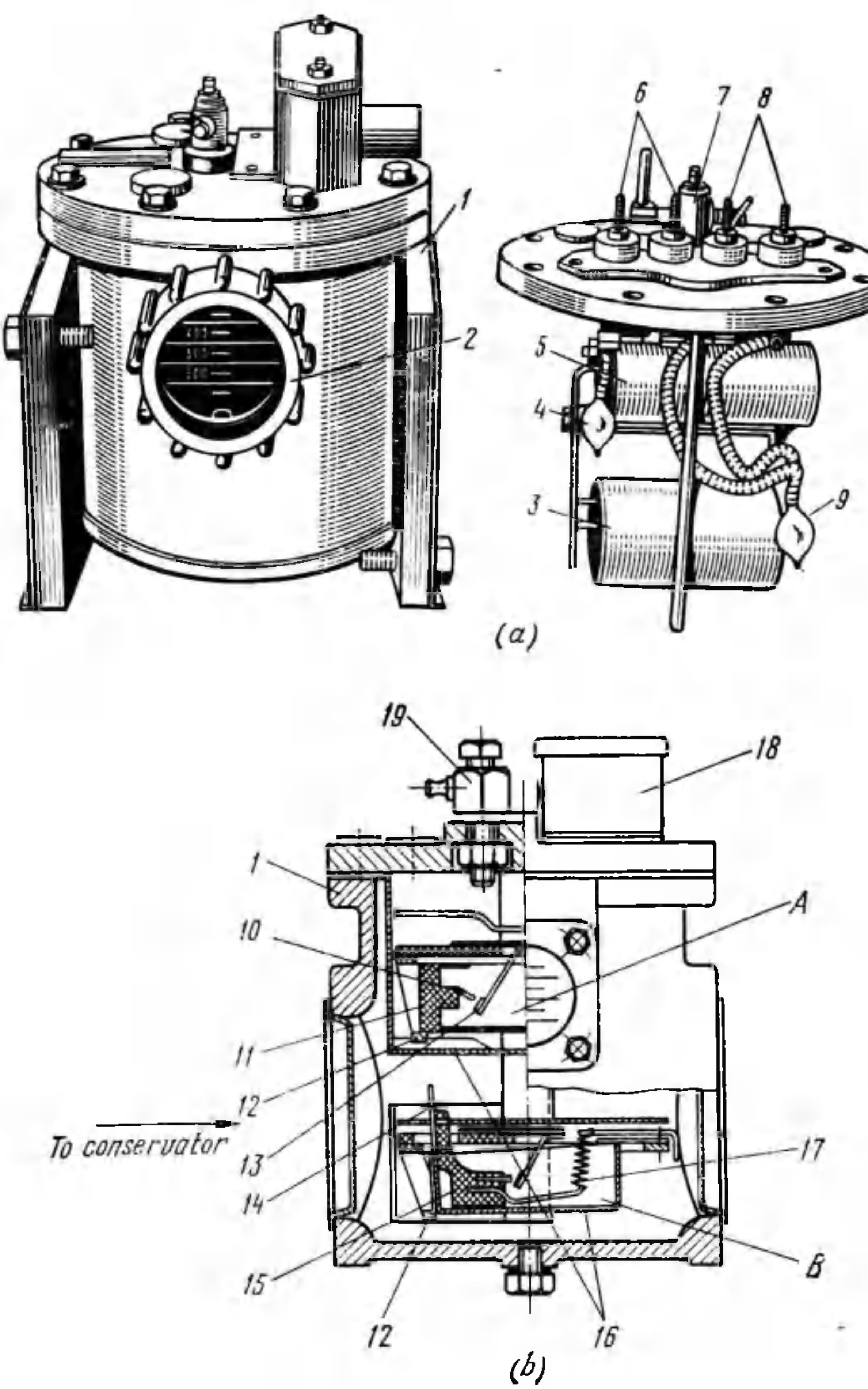


Fig. 3.61. Buchholz relays

(*a*) ПГ-22 float-type relay; (*b*) РГЧЗ-66 cup-type relay

floats carry each a mercury switch, *4* and *9*. Normally, the relay housing is filled with oil, the floats are kept afloat in the oil, and the switches are open. As gas collects in the housing, it forces the oil out of it, the oil level drops, the top float *5* descends, and its mercury switch *4* closes to complete the alarm circuit. In the case of a heavy oil flow into the conservator, the bottom float *5* is turned over, and its mercury switch *9* closes to complete the tripping circuit of the transformer circuit breaker, thereby disconnecting the transformer from the line.

The volume of the gas collected in the relay housing can be read on a scale provided on a sight glass *2* in the housing. The relay cover accommodates alarm terminals *6*, tripping terminals *8*, and a gas-bleed cock *7*.

The РГЧЗ-66 cup-type Buchholz relay (Fig. 3.61*b*), like the float-type relay, has a hermetically sealed metal housing *1* incorporated in the oil pipe connecting the transformer tank to the conservator. The housing contains an alarm element *A* at the top and a tripping element *B* at the bottom. The former responds to the lowering of the oil level in the relay housing below a preset limit, caused either by the accumulation of gas or air in the housing or by oil leakage, and the latter, to the velocity of the oil flow from the transformer tank into the conservator.

The sensitive elements of Type РГЧЗ-66 relay are flat-bottomed, round metal cups *16* which can turn about their pivots *12*. Inside the cups there are insulating supports *11* and *15* which carry movable contacts *10*. The corresponding stationary contacts *13* are held to insulating strips fastened to the relay housing.

When the relay housing is filled with oil, springs *17* cause the top and the bottom cup to turn upwards through an angle of 5 to 10°, and in this position the contacts are open. Should the oil level in the relay housing drop below the preset limit, the torque produced by the weight of the oil remaining in either cup will cause it to turn downwards and thus close its contacts.

To make the lower element respond to the rate of the oil flow from the transformer tank into the conservator, the lower cup is fitted with a vane *14*. The vane is acted upon by a torque which causes the cup to turn and close the trip-

ping contacts when the oil flow rate reaches a preset limit. The relay is supplied with three different vanes to adjust ti to close the tripping contacts at a flow rate of 0.6, 0.9 and 1.2 m/s. The relay is so designed that the sensitive elements are reset automatically after the transformer has resumed normal operation.

After the relay housing is filled with oil and air is released through an air-bleed cock *19*, both sensitive elements must be in the uppermost position and their contacts must be open.

The terminal box *18* for connecting the alarm and tripping circuits does not differ from that of the Type ПГ-22 Buchholz relay. The Type РГЧЗ-66 relay is more resistant to vibration than the Type ПГ-22 (this excluding the possibility of false alarms) and is more reliable in operation.

Along with the Soviet-made Buchholz relays, transformers in this country widely use Buchholz relays manufactured in the German Democratic Republic. These are similar in design to the above-described float-type relay, but differ from it in that their contact systems comprise reed relays actuated by miniature permanent magnets attached to the alarm and tripping floats. Such relays feature high vibration resistance and reliability.

The Buchholz relays respond to any internal transformer faults accompanied by the evolution of gas or lowering of the oil level. Nevertheless, high-capacity transformers are additionally protected by special electric devices (relays) incorporated in protective relay systems.

Spark-Gap Protector

In the case of a failure inside the transformer, such as an insulation puncture between the HV and LV windings or leads, the HV circuit might become connected to the LV circuit with the result that the latter will be under a high voltage dangerous to attending personnel and LV equipment. To prevent this from happening, transformers with a voltage of up to 690 V on the LV side are equipped with a spark-gap protector (Fig. 3.62) which earthes the LV circuit should its voltage rise to a dangerous value. The protector consists of a porcelain housing *1* and a porcelain head *2* screwed into the housing. The housing has two contacts insulated from

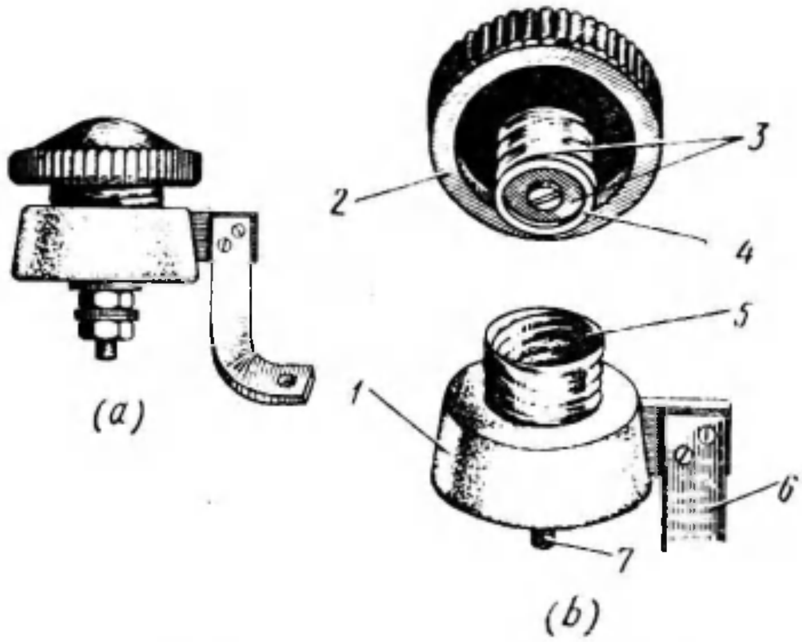


Fig. 3.62. Spark-gap protector

(a) external view; (b) exploded view

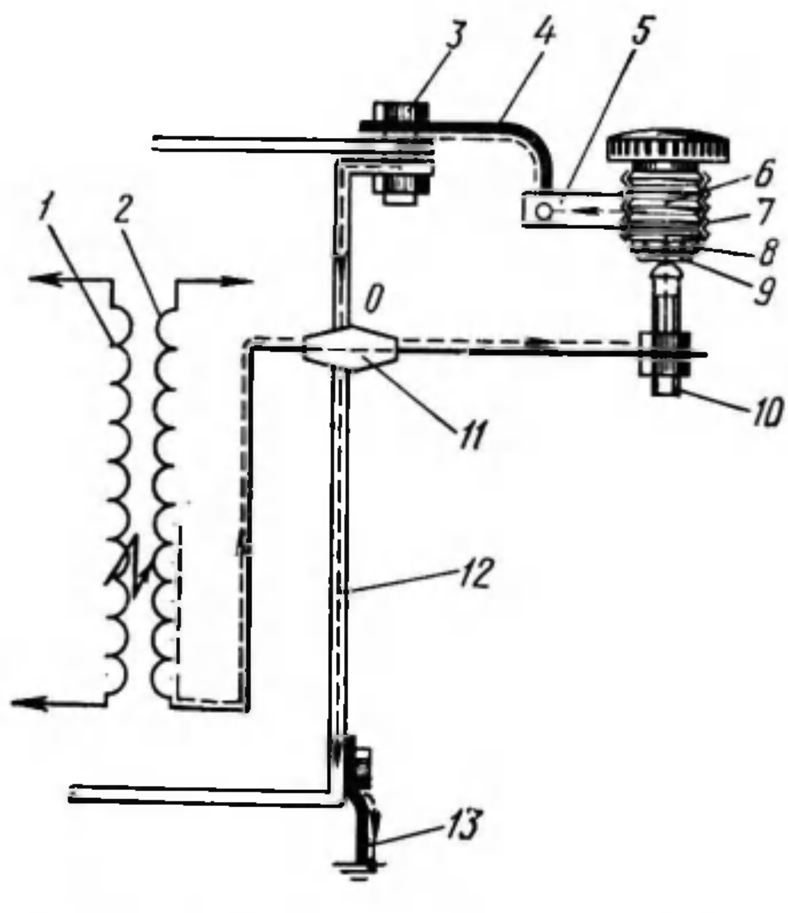


Fig. 3.63. Spark-gap protector connection diagram

1—HV winding; 2—LV winding; 3—tank cover fastening bolt; 4—jumper; 5—mounting bracket; 6—upper head contact; 7—base contact; 8—perforated mica spacer; 9—lower head contact; 10—central contact; 11—neutral terminal bushing; 12—tank wall; 13—tank earthing conductor

each other: the central contact *7* which is connected to the neutral terminal bushing on the LV side of the transformer (if the LV winding is star-connected and has its neutral point brought out) or to a line terminal on the same side (if the winding is delta-connected) and the base contact *5* connected by a mounting bracket *6* to the tank (earth). The head has a contact system *3* consisting of two contacts separated by a mica spacer *4* with perforations forming air (spark) gaps. One of the head contacts touches the central contact and the other, the base contact in the housing.

When the head is screwed into the housing and the protector itself is connected in accordance with the diagram shown in Fig. 3.63, a series circuit to the earth is formed through the mica spacer: LV winding (2)—central contact (10)—lower contact (9) of the head—mica spacer (8)—upper contact (6) of the head—base contact (7)—mounting bracket (5)—tank wall (12)—earth. As soon as the voltage on the LV side rises (due to an insulation failure between the HV and LV windings) to a dangerous level, the air gaps in the perforations of the mica spacer break down and the multiple arc thus formed connects the LV winding to the earth, bringing the winding potential to zero.

The spark-gap protector is installed near the LV terminal bushings, as shown in Fig. 3.1.

Thermometer and Temperature Indicator

In transformers of up to 630 kV A inclusive, the temperature of the top oil is measured by mercury-in-glass thermometers, while in larger units this purpose is served by the Type TCM-100 temperature indicators.

The thermometer is installed on the transformer tank cover in a special pocket, a thin-walled steel cylinder inserted into the tank through an opening in the cover. To protect the thermometer against mechanical damage, it is enclosed in a metal hood.

The temperature indicator (Fig. 3.64) not only reads the temperature of the oil, but also gives attending personnel a warning when the temperature exceeds a preset limit and trips the circuit breaker of the transformer if the oil temperature should rise further.

The indicator operates on the pressure-spring gauge principle. As the oil temperature increases, the vapour pressure of a chemical (methyl chloride) contained in the temperature bulb *3*, which is connected to the case *6* of the instrument by a capillary tube *2*, also increases, this causing a special

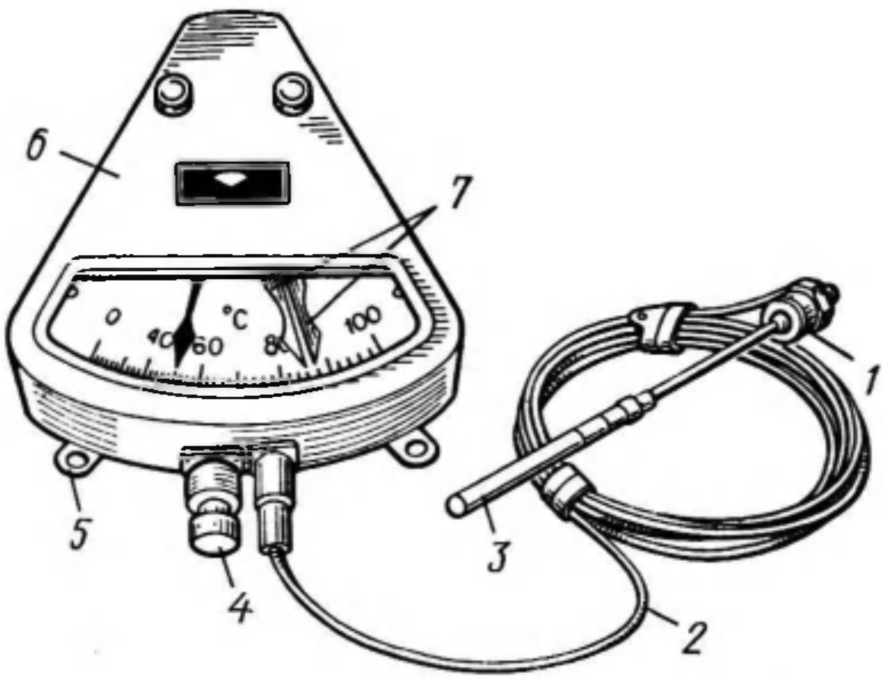


Fig. 3.64. Type TCM-100 temperature indicator

1—nipple; *2*—capillary tube; *3*—temperature bulb; *4*—terminals; *5*—mounting eye; *6*—case; *7*—pointers for setting the alarm and tripping contacts

device (pressure spring or Bourdon tube) installed in the case to actuate a pointer which indicates the temperature on a scale. As soon as the temperature reaches the maximum permissible limit, the contact system of the instrument completes the alarm circuit. Further increase in the temperature causes the tripping contacts to close.

The temperature bulb of the indicator is provided with a nipple *1* for installing it on the transformer tank cover in a special pocket immersed in oil. The instrument is mounted on the tank wall.

Nitrogen Protection of Transformers

The contact of oil with atmospheric air in the conservator leads to the moistening of the transformer insulation and its saturation with oxygen. The electrical and mechanical properties of the moist insulation (pressboard, paper, oil) rapidly deteriorate under the effect of elevated temperatu-

res. To prevent the oil from contacting air, the space above the oil in the conservator is filled with nitrogen. A means for ensuring constant presence of nitrogen in the conservator to exclude the moistening and oxygenation of the transformer insulation is called *nitrogen protection*.

At present, nitrogen protection is mainly used on high-capacity transformers for voltages of 110 kV and upwards.

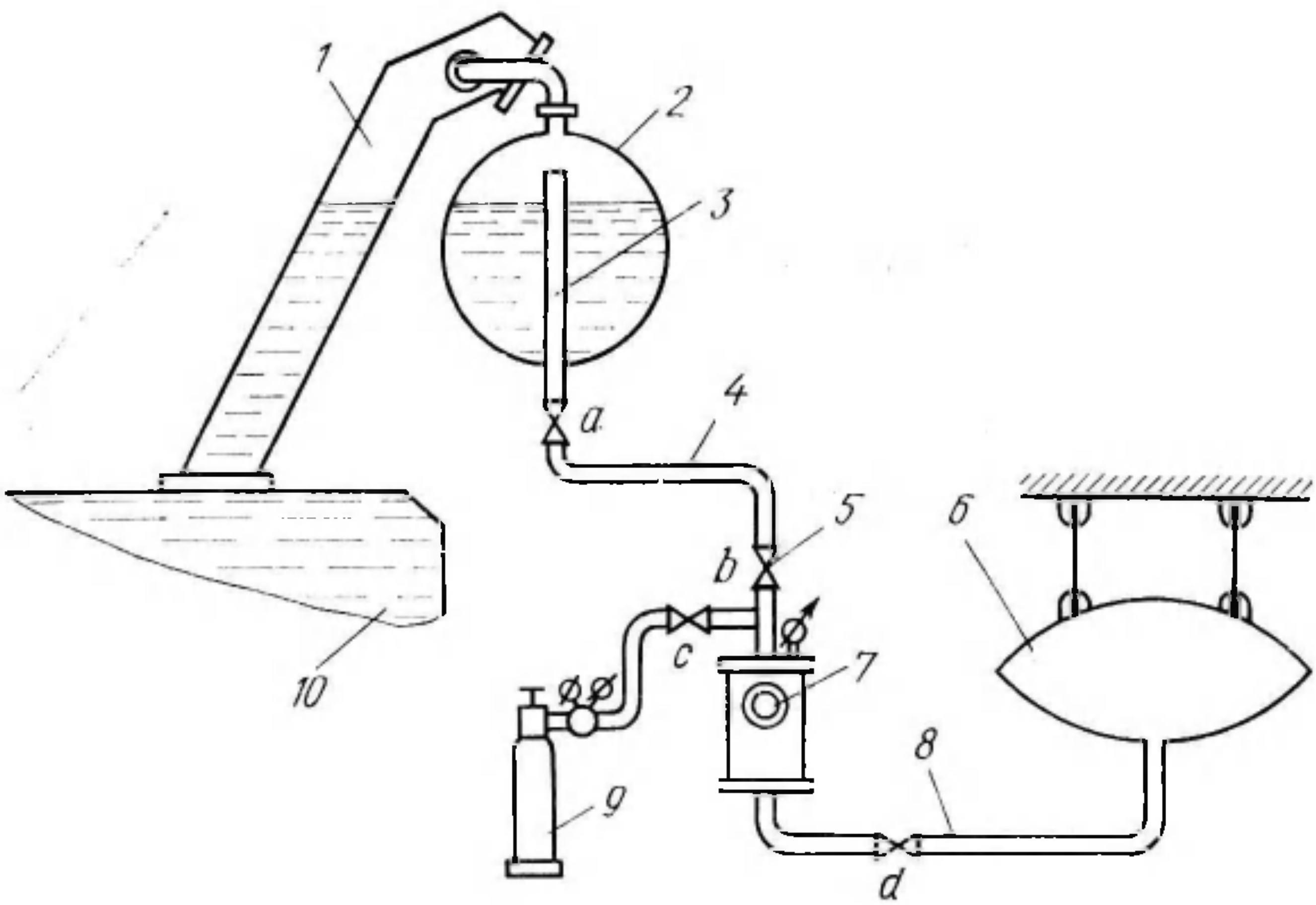


Fig. 3.65. Schematic diagram of a nitrogen-protection system

1—explosion-vent tube; *2*—oil conservator; *3*—breather pipe; *4*—nitrogen pipeline; *5*—valve; *6*—elastic nitrogen-inflated container; *7*—nitrogen breather; *8*—elastic tube; *9*—nitrogen cylinder; *10*—transformer tank

A schematic diagram of such a protective system is shown in Fig. 3.65. In this system, the breather pipe *3* of the conservator is connected via a nitrogen breather *7* to an elastic rubberized-fabric container *6* inflated with nitrogen.

As the oil level in the conservator lowers, fresh nitrogen from the container enters the space above the oil in the conservator, and as the oil level rises, surplus nitrogen is forced back into the container.

The degree of moistening of the silica gel contained in the nitrogen breather is checked by following changes in

the colour of the indicator silica gel as viewed through the sight glass. The breather not only entraps the moisture contained in nitrogen, which may get into it from the oil and solid insulation in the process of their ageing, but also protects the transformer in the event of mechanical damage to the elastic container.

During normal operation, valves *a*, *b*, and *d* are open, while valve *c* is closed. The nitrogen pressure in the system is kept at 0.05×10^4 Pa maximum. Should the pressure drop because of nitrogen leakage, the system is fed with fresh nitrogen from a nitrogen cylinder *9*. To do this, one should close the valves *a* and *b* and open the valve *c*. The nitrogen pressure in the system is checked by means of a pressure gauge installed on the breather.

Prior to filling the system with nitrogen, the transformer should be thoroughly sealed to prevent any nitrogen leakage through the explosion-vent tube, air-bleed valves, nipples, and other transformer fittings mounted on the tank cover.

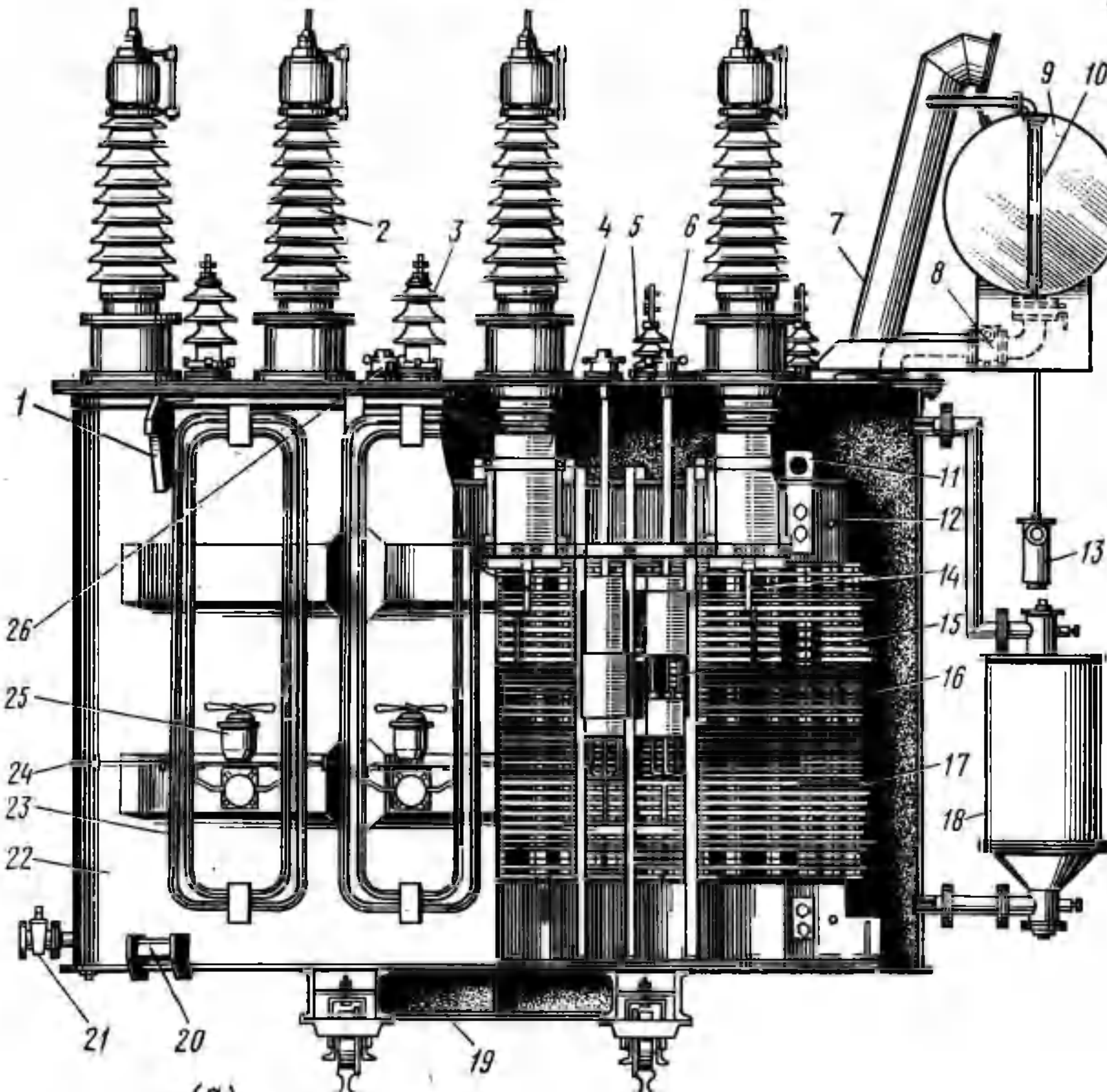
When installing and adjusting the nitrogen-protection system, the procedure is as follows: the transformer is filled with degassed oil, the oil is saturated with nitrogen, the system is filled with nitrogen and then connected to the transformer.

Before filling it with oil, the transformer is evacuated to not higher than 5 mm of mercury. The oil is fed through a degassing unit; the gas content of the oil at the outlet of the unit should be about 0.1% by volume (1 l/m^3) and the moisture content, not more than 0.001% (10 g/m^3).

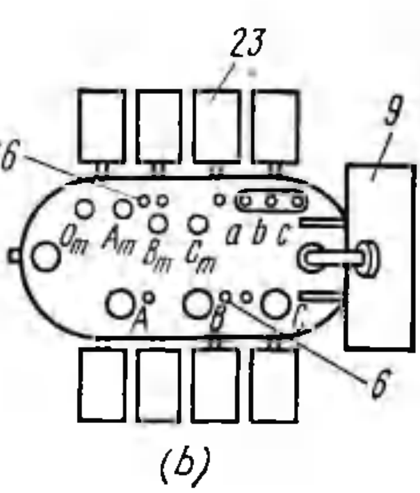
The nitrogen-protection system is set up near the transformer, in a special metal cabinet provided with a bracket for suspending the nitrogen-inflated container.

Film Protection of Transformers

Besides nitrogen protection, there is also what is known as film protection of transformers. It comprises an elastic film placed inside the conservator so that it follows the internal contours of the space above the oil and there is no air in the space between the film and the inner walls of the conservator. As a result, the oil does not contact with the air above the film. As the oil level in the conservator



(a)



(b)

Fig. 3.66. Type ТДТГ-16000/110 three-phase transformer

(*a*) construction; (*b*) plan view; *1*—lifting hook; *2*—HV (110-kV) terminal bushing; *3*—MV (38.5-kV) terminal bushing; *4*—paper-base laminate cylinder of a HV terminal bushing; *5*—LV (10-kV) terminal bushing; *6*—operating knob of the HV tap-changer; *7*—explosion-vent tube; *8*—Buchholz relay; *9*—oil conservator; *10*—oil gauge; *11*—lug for lifting the core-coil unit; *12*—yoke clamp; *13*—breather; *14*—HV line lead; *15*—HV tap-changer; *16*—HV winding; *17*—shielding turns of the HV winding; *18*—thermosiphon filter; *19*—truck on rollers; *20*—jack-mounting pad; *21*—oil drain valve; *22*—tank; *23*—tubular radiator (cooler); *24*—fan-motor wiring; *25*—fan; *26*—operating knob of the MV tap-changer

changes, so does the volume of the elastic container formed by the film inside the conservator, air being either forced out of the conservator or drawn into it through the breather which communicates with the atmosphere via its oil seal. The film is made of an oil-resistant rubberized fabric having low air and moisture permeability.

Film-protected transformers have no explosion vent and use instead a spring-loaded relief vent. The design of the conservator with the protective film does not permit its being exposed to a vacuum, so vacuum filling cannot be used here. Film protection is fairly effective, but it has not found wide application thus far. Almost all of the above-considered transformer components are clearly depicted in Fig. 3.66*a* which shows the Type ТДТГ - 16 000/110 three-phase, three-winding transformer rated at 110 000 $\pm$ 2 (2.5%)/38 500 $\pm$ 2 (2.5%)/10 000 volts. Figure 3.66*b* is the plan view of the same transformer, illustrating the arrangement of the HV, MV, and LV terminal bushings, conservator (9), radiators (23), and tap-changer drives (6 and 26) of the HV and MV windings.

Review Questions

1. Which types of core are used in power transformers? Name the main structural components of the cores.
2. Tell about the construction of the continuous-disk and helical (spiral) windings. How are the lengths (resistances) of the parallel conductors in these windings equalized?
3. What is the purpose of tap-changers? Tell about their design and operation.
4. Describe the construction of oil-filled terminal bushings for 110 kV and upwards.
5. Depict the standard arrangement of the terminal bushings on the cover of the three-phase, three-winding transformers.
6. Tell about the design and operation of the thermosiphon filter and breather.
7. How does the Buchholz relay operate?
8. What is the purpose of the spark-gap protector? Describe its construction and connection.
9. Tell about the construction and purpose of nitrogen protection.

CHAPTER FOUR

Organization of Repair Work

4.1. Types of Repair Work

The latest Soviet-made transformers are capable of working for as long as 25 years, and even longer, without any need for repair, if operated properly. However, the "Guides for Operation of Transformers" envisage periodic repairs of transformers, intended to determine their technical condition and prevent breakdowns. The date of a repair and the scope of work involved depend on the results of preventive maintenance tests, and also on the nature of the defects revealed through visual inspection during operation.

Besides, according to these guides, the main transformers of power stations and substations (i.e., the transformers through which the major portion of the generated electric power is transferred) and also the self-need transformers (i.e., the transformers supplying the consumers on which the operation of the station itself depends) must be opened up after 8 years' service. Furthermore, subject to opening up and inspection are also transformers that for a long period of time have been in transit from the manufacturer to the place of installation.

In the case of a periodic repair, the core and coil assembly is removed from the tank and inspected, and the minor defects detected are eliminated. Periodic repairs are also called planned, because they are envisaged beforehand and included in the plan of major transformer repairs.

In addition, the power industry still uses a relatively large number of old transformers of the Soviet and foreign makes, which usually require either a repair involving the replacement of the windings and insulation or complete restoration including the reinsulation of the core laminations.

In some instances major transformer repairs are caused by damages due to accidents. Accidents result mainly from

excessive overloads, moistening of insulation, loosening of contacts, atmospheric voltage surges, and weak clamping of the windings.

Sometimes, destructions due to accidents are so heavy that transformers can hardly be renewed, this requiring much time and great material expenses.

The scope of repair work depends on the technical condition of a given transformer and the character of its failure. It is customary to subdivide transformer repairs into minor (maintenance or servicing), medium (inspection), and major (overhaul).

Minor repair is a purely preventive work of narrow scope carried out without opening up the transformer. It includes external inspection, detection and elimination of minor defects in fittings, cooling system, and hang-on devices, tightening up of fastenings, elimination of oil leaks and adding oil to capacity, wiping of external surfaces, checking of winding insulation resistance, and other minor operations. Minor repair work is carried out by the operating personnel of power stations and substations.

Medium repair involves the opening up of the transformer and removal of the tank from its bottom (bottom-split transformers) or withdrawal of the core-coil assembly from the tank (top-split transformers). This type of repair includes inspection and minor repair of accessible internal assemblies, and also repair or replacement of individual devices or components (e.g., conservator oil-pipe connection, tap-changer, cooler, oil valves, etc.). It is carried out with the transformer being de-energized for a relatively short period of time. Such repair work is usually necessitated by internal defects revealed in service, that may cause a major breakdown.

Minor and medium repairs fall into the category of planned repairs whose execution dates are envisaged by appropriate operating and servicing instructions. In transformer repair practice, medium repair is customarily referred to as inspection. The duration of inspection involving the opening up of the transformer, and also, conditions for its execution are specified in repair instructions.

Major repair involves replacement of the windings and insulation, reinsulation of the core laminations, resoldering

of the winding connections, and other operations (including those of re-design) that require complete disassembly of the core and rewinding of the windings.

4.2. Preparation for Repair and the Organization of Repair Work

Before starting repair, it is necessary to determine the scope of the work to be carried out. If the transformer is in actual service, one should, before putting it out of operation, draw up a register of the necessary work on the basis of the defects that have been detected by visual inspection and tests. Such a register containing a draft list of the repair operations required serves as an initial document for determining the necessary labour force, repair time, materials, spares, tools and accessories. The scope of additional work (if required) is revealed by inspection after opening up the transformer.

As a rule, major repair work on high-capacity transformers is carried out directly on site. For this purpose, power substations are provided with special repair towers equipped with electric hoists. At power stations, such a repair is carried out in a machine-room equipped with a bridge crane. Low-capacity transformers (Size I and II) are either repaired directly on site or shipped to specialized repair works. Inspections have sometimes to be carried out at temporary premises, and sometimes even outdoors. Large units are usually repaired by specialized organizations having available skilled repairmen going directly to the place of installation of the transformers.

Actual repair is preceded by some preparatory and organizational work. First of all, suitable premises are selected which must be protected against dust and precipitation, and must be equipped with hoisting mechanisms or must permit suspension of such mechanisms. There must be enough space to accommodate the tank of the transformer, its core-coil assembly, shelves for dismantled assemblies and components, a workbench, oil purifying apparatus, materials, appliances, scaffolds, ladders, and other equipment. The premises must have an electric service board, must be well

lighted and ventilated, and must meet all fire preventing requirements.

Hoisting mechanisms and installations are of special importance. They must ensure safe work and facilitate laborious operations. Hoisting mechanisms (electric winches, bridge cranes, hoists) must be installed and checked by the beginning of repair work, and if their running test dates are overdue, they must be tested in accordance with accident pre-

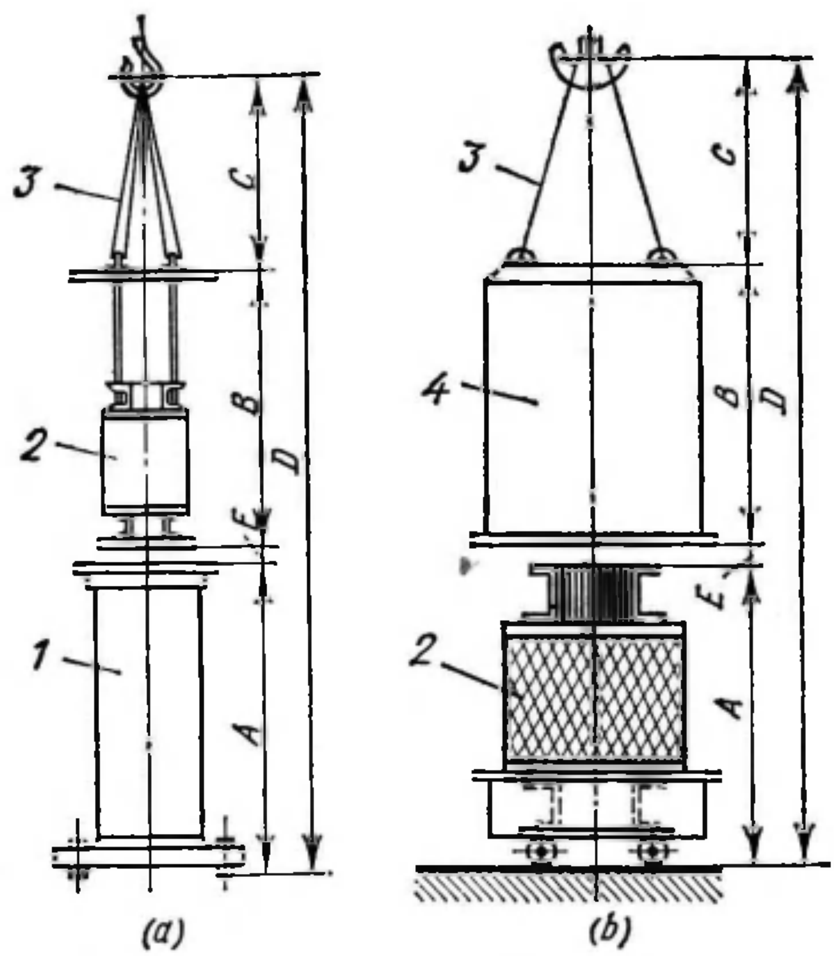


Fig. 4.1. Sketch on opening up the transformer

(a) lifting the core-coil assembly; (b) lifting the bottom-split transformer tank; 1—tank; 2—core-coil assembly together with the tank cover; 3—wire-rope slings; 4—bottom-split transformer tank

vention requirements. The load-lifting capacities of the mechanisms, slings, and wire ropes are selected according to the mass of the given transformer, which is indicated in its nameplate and certificate.

When removing the core-coil assembly from the tank, hoisting mechanisms are hung at such a height as to ensure that the distance D from the hook to the floor (Fig. 4.1*a*) is not less than the sum of distances $A + B + C + E$. The sizes A and B are taken from the manufacturer's specifications or from the transformer drawing, the distance E is taken at 100 to 150 mm. The distance C is determined by the length of the slings *3* selected. A similar sketch (Fig. 4.1*b*) is drawn prior to lifting the tank of bottom-split transformers.

Depending on the type of repair and the type and capacity of the transformer, use is made of various tools, appliances and materials, which not always can be promptly manufactured or received during repair. To avoid delays, such equipment and materials are delivered to the repair ground beforehand. For example, by the beginning of a major repair involving the replacement of the windings one must prepare metal scaffolds, platforms, an appliance for removing and mounting the windings, an electric-brazing apparatus, slings for lifting the transformer and its core-coil assembly, an oil pan for the core-coil assembly, basic materials, and spare parts.

Much preparatory work is involved in the treatment of transformer oil. In medium and major repairs, used oil has to be either replaced by fresh oil or purified. Therefore, it is necessary to bring fresh oil and oil-purifying apparatus near the repair ground, lay oil pipelines, prepare a vessel for used oil, install the purifying apparatus (centrifuge, filter press, zeolite dehydrator plant) and connect it to mains. Here, special attention must be paid to fire preventing measures, and the workplace must be provided with fire fighting equipment.

When repairing large transformers directly at the place of their installation, a team of repairmen have to do all the necessary work from the beginning to the end. It is much more difficult than to perform the same work at a specialized repair plant, where different operations are performed by workers of different trades, stationed at permanent workplaces provided with stationary means of mechanization. Under conditions of individual repair, the workplaces of repairmen are located at the repair site to which the transformer is brought. Depending on the type of operation to be performed, an electrician-mechanic periodically changes his workplace, but the major part of his working time he spends at the core-coil unit, tank, or workbench.

The quality and productivity of repair work largely depend on the maintenance of the workplace by the electrician-mechanic. When tools, appliances, and materials are placed correctly at the repair site, the labour consumption is minimized, waste of time is avoided, and safe work is ensured.

To keep the workplace in proper order, one must see to it that there are only those tools and materials which are necessary to do the given job. The tools and materials must be within easy reach, those used more frequently being placed closer. Various tools and appliances must be put in different drawers of the workbench: small tools which are used more frequently must be in the upper drawers, while heavier, which are used rarely, in the lower ones. Bulky devices must be placed on shelves and at specially allotted places. Measuring instruments must be kept in a special drawer, in boxes or cases, and must be wiped, slightly oiled and put in place after being used. At the workplace, tools must be placed in a strict order, they must never be put one upon another or on other articles and must be protected against impacts and dirt. Once the work is ended, all the tools, appliances and materials must be put away.

The workbench must be equipped with a drill press, an electric tool grinder, and a vise, and must be provided with a complete set of tools and appliances necessary for repair. Materials must be kept in individual closets or boxes, spare parts, on shelves. Technical papers are to be kept in a desk drawer or a bookcase.

At the workplace, near the core-coil unit and tank, there must be receptacles for connecting portable lamps operating at a lowered, safe voltage.

Repairs of large, high-voltage transformers involve a large number of disassembly-reassembly, special, and hoisting operations which are to be carried out in a certain definite sequence and in strict compliance with the established techniques. To ensure that all repair operations are carried out at a high technical level and with the shortest possible delay, a *plan of organization of repair work* is drawn up. This plan is worked out several months before the beginning of the actual repair work, so that there is enough time to carry out all the preliminary operations envisaged.

The plan includes a brief description and specifications of the given transformer, including its characteristics, dimensions, masses of assemblies and components, and specific features; a list of the necessary technical papers; the repair work register; a repair process chart indicating the labour consumption in each job, a list of the required materials,

tools and equipment; a repair schedule giving particulars as to the trades and skills of the required personnel and the number of shifts; a plan of preparatory operations, including their complete list and dates of execution; a list of spare parts and materials, indicating their grades, sizes, type designations, drawings, suppliers, and delivery dates; a list of industrial equipment, tools, and appliances, drawings of nonstandard mechanisms, devices, and special tools; the repair ground layout showing the disposition of the equipment, mechanisms, appliances, spare parts, transformer assemblies, and accessories; a list of the necessary guiding papers including instructions, drawings, technological recommendations, etc.

The problems associated with the delivery of the transformer to the repair ground and back to its foundation, which involves the most labour-consuming hoisting operations, are also considered in detail in the plan of organization of repair work.

The actual repair work starts after all the preparatory operations envisaged by the plan are carried out.

4.3. Specific Features of Transformer Repair Work. Conditions of Opening Up the Transformer for Inspection

Irrespective of the type and purpose of transformers, the main operations for all types of their repair are common. During repair, each transformer, its assemblies and fittings are disassembled, inspected, rejected if unfit, repaired, and reassembled. When disassembling and inspecting assemblies and components, one determines whether they are fit, or whether they can be repaired. The process of repair involves the renewal and replacement of components. The reassembly of the transformer after repair is carried out in consecutive order opposite to that of disassembly, and each operation is controlled by measurements and tests.

The operations and methods of work used when repairing transformers are defined in workshop instructions which are either analogous to those adopted at transformer-building works or approximate them as closely as possible. Strict observation of the established technological discipline and rules stipulated by the instructions is the indispensable condition

of the high quality of repair and the minimum expenditure of means and time. The repair technique can only be varied if this improves the quality of work and reduces labour consumption. However, any changes in the technique must be approved by the managerial staff responsible for repair and must be registered officially.

Much importance is attached to the conditions of opening up the transformer for inspection and repair. After the transformer has been put out of service for repair, it is tested, prior to opening up, in order to determine the moisture content of its insulation. Usually, transformers that have been in actual service immediately before repair have their insulation dry and so require no drying out when being inspected. To avoid moistening of the insulation during inspection, the core-coil assembly is permitted to be out of oil for not longer than the standard period of time (see Table 4.1).

Table 4.1

Maximum Permissible Duration of the Transformer Core-Coil Assembly Being Exposed to Air

Transformer specifications	Maximum duration of core-coil assembly exposure to air, h			
	at temperatures above 0°C and relative humidity of ambient air, %			at temperatures below 0°C
	up to 65	65 to 80	more than 80	
Transformers for voltages up to 35 kV inclusive, having capacity below 10 000 kV A	24	16	12	12
Transformers for voltage of 35 kV, having capacities of 10 000 kV A and over, and also all transformers for voltages of 110 kV and over	16	12	8	8

An oil-immersed transformer can be opened up for inspection only if the temperature of its core-coil unit is equal to or higher than the temperature of the ambient air. Should the core-coil unit be colder than the ambient air, the opening up of the transformer must be postponed for a period of time sufficient for the temperatures to equalize, or the core-coil unit must be heated up. This requirement is explained by the fact that when warm air comes into contact with the cold core-coil unit, moisture contained in the air condensates on the surface of the unit and moistens the insulation.

As long as the core-coil unit is out of oil, its temperature must exceed the dew point of the ambient air by not less than 5°C and in any case, it must not be lower than 10°C. Sometimes it proves necessary to heat up the transformer in order to meet this condition. The dew point of the ambient air as a function of its temperature and humidity is determined from relevant tables. If the ambient humidity is in excess of 85%, the transformer is permitted to be opened up only in a room where the necessary conditions can be created.

The temperature of the core-coil unit is measured by means of the temperature indicator or a thermometer placed on the top yoke through an inspection hole in the tank cover. Mercury thermometers are not used for this purpose for fear of mercury getting into the transformer should the thermometer be broken accidentally. In Size I through III transformers, there are no inspection holes in the tank cover, therefore, the temperature of the core-coil unit is judged by the top oil temperature which is measured with a thermometer placed in a special pocket provided on the cover.

The time of the core-coil unit staying out of oil during inspection can be doubled as compared with the figures given in Table 4.1, provided that the ambient temperature is above zero, the ambient humidity is below 80%, and the temperature of the core-coil unit is constantly maintained at not less than 5°C above the dew point of the ambient air and in any event, is not lower than 10°C. The relative humidity of air is measured with a psychrometer. This may be the wet-and-dry-bulb-thermometer type, in which case the percent humidity is found from the reading of the wet-bulb thermometer and the difference between the readings of the dryand wet-bulb thermometers, using a psychrometric table.

Review Questions

1. What are the preparatory operations to be performed before repairing the transformer?
2. What are the conditions to be met when opening up the transformer for inspection?
3. What is the duration of the core-coil unit exposure to air during inspection?
4. How is one to maintain one's workplace properly?

CHAPTER FIVE

Medium Transformer Repair (Inspection)

5.1. Disassembling the Transformer

For disassembly, the transformer is brought to the repair ground and placed under the hook of a hoisting mechanism. If the transformer is equipped with detachable coolers (radiators), the latter are dismantled and repaired directly at the place of installation of the transformer. Sometimes, the radiators or their individual components are repaired at a shop. Prior to disassembly, the transformer is carefully inspected on the outside with a view to detecting external faults, such as oil leaks and mechanical damages to the tank, oil conservator, and terminal bushings, and evaluating the condition of the sealing cement and flanges of the terminal bushings, and seals, and the serviceability of the spark-gap protector, oil gauge, and thermometer. The defects detected are entered in the register of the transformer technical condition.

After that, the thermometer, temperature indicator, spark-gap protector, and alarm and tripping circuits are dismantled, using a screw driver and a wrench. When removing the temperature alarm, the hose with the capillary tube is carefully wound into a coil without making sharp bends.

Then the external surface of the transformer is cleaned. If very dirty, it is cleaned with steel scrapers, wire brushes, and rags wetted with a solvent. Depending on the transformer height, this work is done while standing on the floor or on platforms and scaffolds. Sometimes, only the cover is cleaned before disassembly, the rest of the tank surface being cleaned while repairing the core-coil unit.

If, during inspection and cleaning, oil leakages through welds, flanged joints or at other places are detected, then to determine the defect more accurately, the transformer is

subjected to an excessive oil pressure. After that, oil is drained off partially or completely.

Oil is drained off partially if the day the external devices are dismantled and the tank cover unfastened, the withdrawal of the core-coil unit from the tank is not contemplated. Thus, the time of the core-coil unit staying in air is reduced. Oil is drained off only down to the level of the top yoke of the core, so as to ensure that the insulation and windings remain submerged in oil.

Oil is drained off completely when it is contemplated to end the repair of the core-coil unit and the tank at one go, or when the core-coil unit must be dried out. Oil is drained off through the bottom valve of the tank by means of a pump. In Size I and II transformers, oil is usually drained off by gravity. Rubber hoses or steel pipes 30 to 50 mm in diameter serve as conduits when draining oil.

If oil can be used for further operation, it is drained into a clean transformer-oil vessel or into a specially cleaned dry vessel provided with a cover that can be closed hermetically. Spoilt oil is drained into waste-oil containers.

To withdraw the core-coil unit from the tank, the transformer is positioned so as to ensure that the hook axis of the hoisting mechanism passes through the centre of gravity of the transformer. In this case the core-coil unit does not brush against the tank walls when being lifted and lowered.

After that, the nuts and bolts of the fittings installed on the tank cover are undone. For this purpose use is made of double-ended, monkey, and socket wrenches. Most popular are double-ended wrenches having at each end a mouth corresponding to a standard bolt head or nut.

The most frequently used standard sizes of double-ended wrenches and the corresponding sizes of bolts are as follows:

Wrench size, mm	14	17	19	22	24	27	30	32	36	41	46	55	65	75	80	85
Bolt size, mm	8	10	12	14	16	18	20	22	24	27	30	36	42	48	52	56

Monkey wrenches are divided into six numbers—from No. 1 to No. 6. No. 1 wrench has a jaw span of up to 19 mm, No. 2 wrench, up to 30 mm, No. 3 wrench, up to 36 mm, No. 4 wrench, up to 41 mm, No. 5 wrench, up to 46 mm, and No. 6 wrench, up to 50 mm.

The labour consumption in fastening and unfastening bolted joints can be considerably reduced through the use of pneumatic nut runners.

The unfastening of the bolted joints of transformers having no oil conservator, explosion-vent tube, and other fittings on the tank cover is started from the detachable joint between the cover and tank. Where such fittings are installed on the tank cover, the disassembly of the transformer is started with their dismantling.

First the Buchholz relay and then the explosion-vent tube and the oil conservator are dismantled. To remove the relay, it is necessary to undo the bolts (four on each side of the relay) which hold the flanged connections of the relay. When doing this, the relay is supported by hand, or a wooden block is placed under it. After the bolts are removed, the relay is displaced parallel to its flanges and removed. The holes in the relay body are closed with temporary blind flanges of pressboard which are secured in place with the released bolts. Then the relay is carefully placed on a rack or is immediately sent to a laboratory for inspection and tests.

After that, the explosion-vent tube is unfastened and dismantled. In Size III and IV transformers, the tube is dismantled by two men, one standing on the tank cover and supporting the tube and the other undoing the nuts which secure the lower flange and the steel brace or bracket of the tube. Then the tube is lifted a little with a hemp or wire-rope sling and lowered on the floor.

The oil conservator is dismantled in the following order: first, the oil pipe connecting the conservator to the Buchholz relay is removed, then the glass of the oil gauge is closed with a temporary shield of boards or plywood, which is tied to the oil gauge connections, the conservator is slinged with a hemp or wire-rope sling (depending on the mass of the conservator), the brackets of the conservator are unfastened from the tank, and the conservator is lowered on the floor. In large transformers, the conservator vessel is provided with special lugs for slinging. Such conservators are dismantled by means of a hoisting mechanism. Truck cranes are frequently used for this purpose when repairing transformers at substations.

To protect the transformer tank and oil conservator against the ingress of dirt and moisture, all openings in the tank cover and conservator are closed with blind flanges. Old rubber gaskets are used for sealing these flanges. All the disassembly operations on the transformer tank cover should be carried out with great care in order not to damage the porcelain insulators of the terminal bushings and the glasses of the oil gauge and Buchholz relay.

Then the bolts fastening the tank cover are undone. This operation is performed by means of two wrenches, one of them being used to undo the nuts under the cover flange and the other, to prevent the bolt heads from rotation. If the bolts are badly rusted, it is necessary to wet them with kerosene beforehand. After the bolts have been removed from the holes, they are made complete with washers and nuts and then placed in buckets or boxes and wetted with kerosene.

The next, most important operation is the slinging of the core-coil unit and its withdrawal from the tank. For this purpose, the tank cover is provided with lifting lugs which are screwed on the protruding ends of the lifting rods fixed to the top yoke clamps. Transformers up to 400 kV A in capacity usually have two lifting lugs, while larger units are provided with four lugs. Slings of the appropriate lifting capacity are put on the hook of a hoisting mechanism and on the lifting lugs, and special steel rods are then passed through the holes in the lugs. To avoid bending of the lifting rods, slings of the appropriate length are to be used and the lifting lugs are to be screwed home.

Then, using the hoisting mechanism, the transformer cover together with the core-coil unit which is connected to it is carefully lifted a little. When doing this, attention should be paid that the steel rods and slings are not out of engagement with the lifting lugs and that the slings are tensioned equally.

As soon as the cover is just separated from the tank flange and the core-coil unit is slightly lifted, one should stop the lifting and see that the cover together with the core-coil unit is not displaced relative to its initial position on the tank. If the core-coil unit is inclined and there is a possibility of its brushing against the tank, it is necessary to

lower it back in place and check once more the correctness of slinging, i.e., check that the lengths of the slings are equal and the position of the hook relative to the centre of gravity of the transformer is proper.

To make sure of the reliable operation of the hoisting mechanism and its brake, the core-coil unit is lifted 100 to

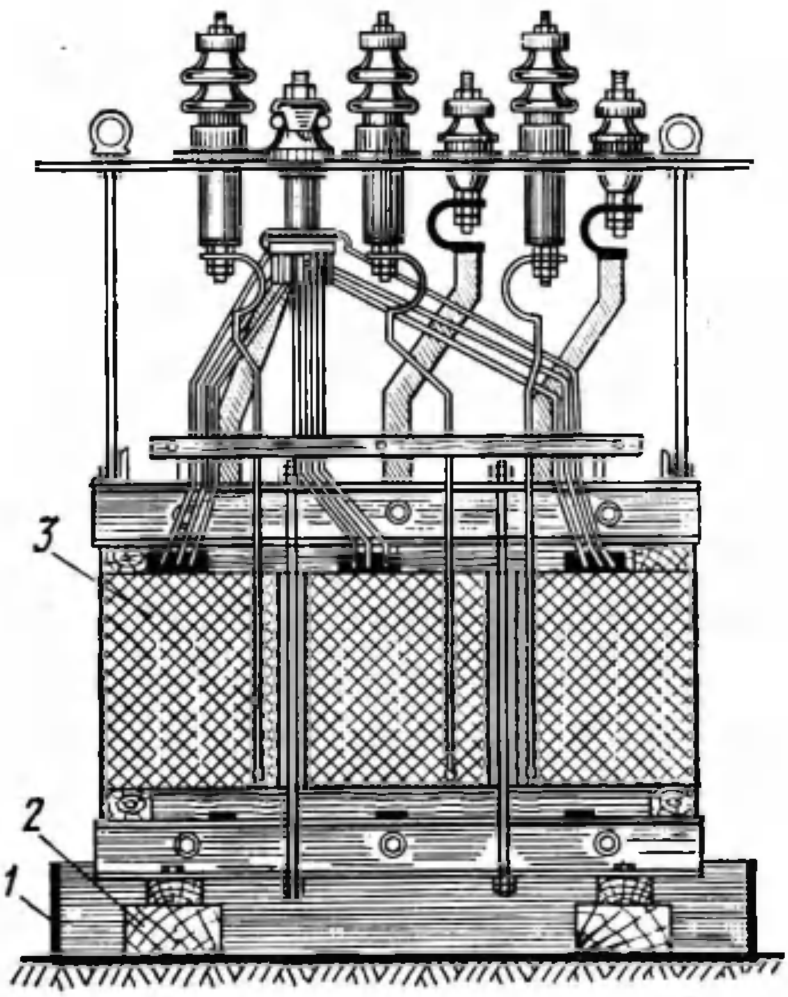


Fig. 5.1. Placing the transformer for inspection (view from the HV side)

1—oil pan; *2*—wooden block; *3*—core-coil unit together with the transformer cover

200 mm and held suspended for a few minutes and then lowered on the tank bottom.

If oil has been drained off partially or completely, the core-coil unit is lifted up to a level convenient for washing it above the tank. Before washing, one should inspect the core-coil unit, paying attention to sludge and dirt deposits in the windings, on the core steel, and in the oil ducts.

The core-coil unit is washed with a jet of warm, clean oil from a rubber hose. The washing begins from the top and gradually goes down as the core-coil unit is lifted. When washing, one should try to flush thoroughly the oil ducts in the windings and core, as well as all accessible units and parts of the transformer.

After the washing has been finished and the washing oil has drained off, the core-coil unit is lifted 50 to 60 mm above the top tank frame. If the hoisting mechanism can move horizontally, the core-coil unit is conveyed to a specially prepared floor where it is lowered on wooden planks placed in an oil pan, but if the hoisting mechanism cannot travel, the tank is then moved aside, an oil pan *1* (Fig. 5.1) is put in its place, and the core-coil unit *3* is lowered in this pan. When repairing transformers under works conditions, the core-coil unit is lowered on a floor provided with a grating for draining the remainder of the washing oil into an oil-collecting vessel. The lowered core-coil unit must occupy stable vertical position without any inclination. Then the slings are released and the repair work on the core-coil unit, tank cover, and other transformer units is started. Usually, the core-coil unit and the tank are repaired simultaneously in order to keep the unit in air for as short a period of time as possible. As soon as the core-coil unit is ready, it is installed in the tank and the tank is immediately filled with oil.

5.2. Repairing the Windings

The repair of the windings begins with their inspection with a view to checking them for tightness of axial clamping, their deformation and displacement relative to the normal position, the presence of sludge in the oil ducts, the condition of the soldered joints and contacts in the lead connections, and the condition of the interturn insulation, i.e., its integrity, mechanical strength, and colour. In the process of long-term operation, the axial clamping of the windings somewhat weakens, mainly as a result of the shrinkage of the pressboard and paper insulation (spacers, interturn insulation, end-winding insulation) on drying. Also, there occurs some reduction of the axial dimensions of the coils and the end-winding insulation, caused by shocks due to short circuits in service. This reduction may also result from the fact that the possible clearances in the interturn and end-winding insulation of stacked-up and riveted pressboard components are sometimes not taken up completely when clamping the windings during assembly.

Weak axial clamping of the windings may lead to their destruction in the event of short circuits causing heavy mechanical forces, especially axial, between the coils. This condition can easily be detected through the reeling of the insulating strips, spacers, and other components when trying to displace them by hand, and to eliminate it, the windings are compressed between the yoke clamps (in Size I to III transformers) by tightening the nuts on the vertical tie-rods *5* (see Fig. 3.10).

Sometimes, should the axial clamping of the windings be weakened substantially, the top yoke is unclamped by loosening the nuts on the yoke studs and vertical tie-rods, and additional insulation in the form of slotted rings and spacers is inserted into the windings. If the HV and LV windings differ in the axial size so that the inner coils are clamped badly, the additional insulation should be made to compensate for this difference. Then the windings are clamped by tightening the nuts on the tie-rods and after that, the nuts on the clamping studs of the top yoke are tightened. After the clamping is finished, it is necessary to measure the insulation resistance of the clamping studs by means of a megohmmeter.

In transformers having no special devices for clamping the windings, the latter are pressed, if necessary, by packing out, i.e., by driving additional insulating spacers—wedges—between the coil-end and yoke insulation at the top of the windings. These wedges are made of preliminarily dried pressboard or paper-base laminate. All stacks of interdisk spacers are packed out uniformly around the circumference of the windings by turns, one stack after another. The packing out is done with the aid of an auxiliary wooden wedge which is driven between the spacers in one stack to loosen the spacers in the adjacent stacks so as to permit additional insulating spacers to be driven between them. Then the wooden wedge is removed and the next stacks of the interdisk spacers are packed out in the same way. The wedges are driven in with a hammer, and to prevent their ends from splitting, one should use a pad made of wood, pressboard, or fabric-base laminate.

Quite frequently it happens that the outer windings are slackened much greater than the inner ones and have a

smaller axial size. In this case additional insulating strips are driven between the main interdisk spacers of the outer windings. This operation should be carried out with great care and attention, so as not to damage the interturn insulation. It is impermissible to drive additional strips between an interdisk spacer and the surface of the disk itself, since this may result in a damage to the interturn insulation.

The packing-out of the windings should be carried out with the slings being kept taut, for in this case the wedging

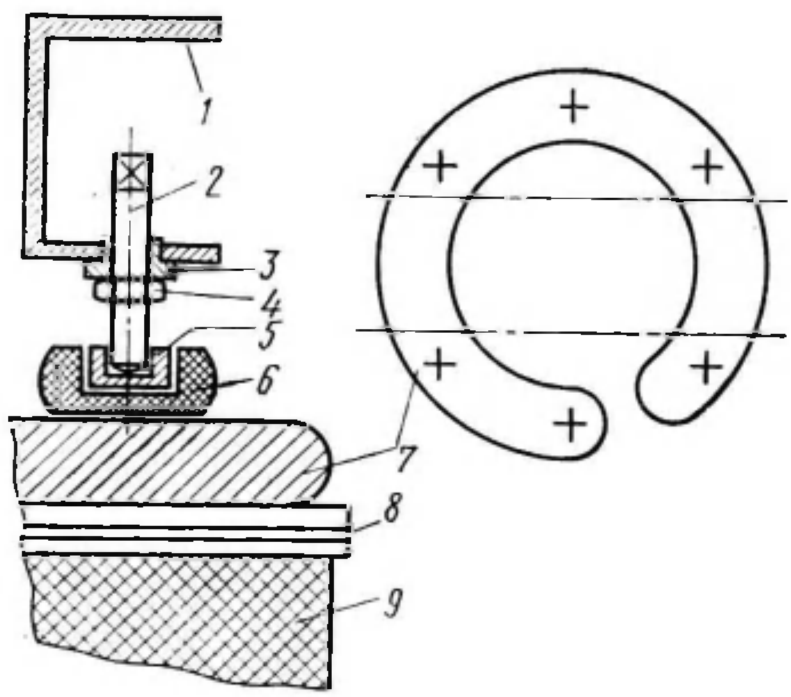


Fig. 5.2. Axial clamping of the windings with pressure rings

strips can be driven in somewhat easier. When packing out the windings, one should observe the following rules: the packing-out must be uniform and tight over all the vertical stacks of spacers and the circumference of the windings (the wedges must not move when trying to displace them by hand); all the stacks of interdisk spacers must be strictly vertical and free from displaced spacers; the additional strips must run the whole length of the main spacers and not be displaced relative to them; after packing out, the axial dimensions of the HV and LV windings must be as close as possible.

In dry-type transformers of more than 160 kV A in capacity and in oil-immersed transformers of Size III and upwards, the axial clamping of the windings is effected by means of steel pressure or end rings and clamping screws installed in the flanges of the top yoke clamps (Fig. 5.2). A flat steel pressure ring *7* is placed on the coil-end insulation *8* of the

windings *9*. The ring is slotted in order not to form a closed turn. Round collar bushes *3* into which the clamping screws *2* are driven, are welded into the flanges of the top yoke clamps *1*. Should the screws press directly upon the pressure ring, a short-circuited turn would be formed. To insulate the steel ring from the yoke clamps, use is made of plastic or laminate (fabric- or paper-base) supporting saddles *6*. The saddles are provided with steel inserts *5* which protect them from breakage by uniformly distributing the pressure exerted by the screws when they are being tightened. Lock nuts *4* prevent the clamping screws from working loose during operation or shipment of the transformer. To ensure uniform clamping of the windings, 4 to 6 clamping screws are used for each end ring; high-capacity transformers may use even a greater number of clamping screws.

In transformers for voltages up to 110 kV, all the windings placed on one and the same core limb are mainly clamped with a single, common pressure ring, while in those for 220 kV and higher, each winding is clamped with a pressure ring of its own. Each pressure ring is earthed by means of a flexible jumper which connects it to the top yoke clamps. Lately, much work has been done to replace the steel pressure rings by plastic ones in order to save metal and decrease power losses in the rings.

During inspection, the axial clamping of the windings provided with pressure rings and clamping screws is improved in the following order: first the lock nuts are slackened uniformly in a crisscross order, i.e., every other nut is slackened across the diameter from, rather than next to, the previous one, then the clamping screws are driven in as far as they will go in the same order, and finally, the lock nuts are retightened. After that, the fastenings of the earthing jumpers that connect the pressure rings to the top yoke clamps are tightened up, the insulation resistance of the pressure rings with respect to the yoke clamps and core steel being preliminarily measured with the earthing jumpers disconnected from the yoke clamps.

When inspecting the windings, the interturn insulation is checked for damaged spots, and if there are any, the turns at these spots are additionally insulated. This operation is carried out using a preliminarily dried tape made of

Grade ЛХММ-105 oil-resistant varnished cloth, which is passed between the coil turns. If the interturn insulation is sufficiently strong and elastic, the outer turns at the place where their insulation is to be renewed can be moved apart with a pressboard wedge to facilitate the passage of the tape. Should the interturn insulation be damaged at a place far

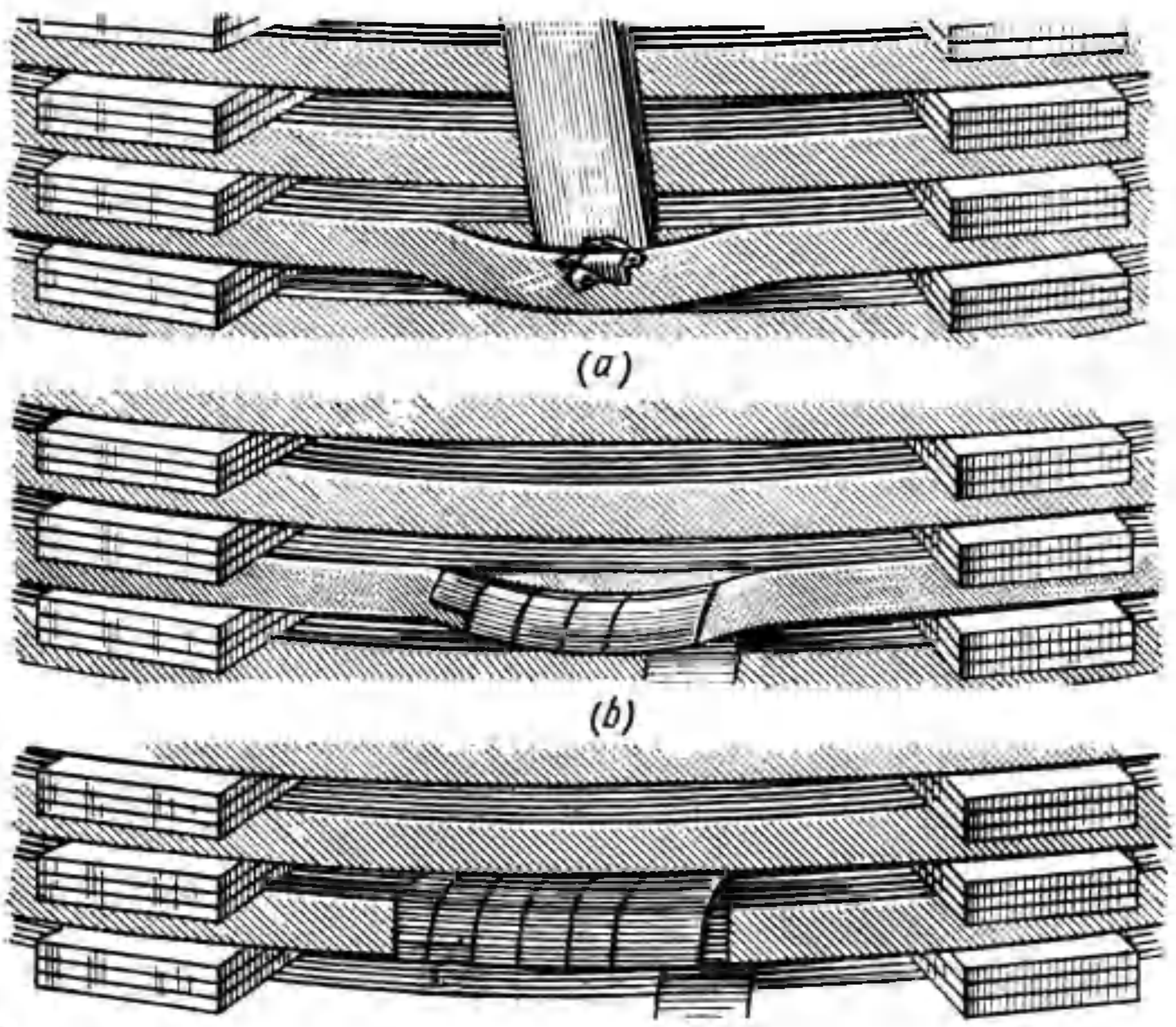


Fig. 5.3. Sequence of the renewal of damaged interturn insulation
(a) separating the turns with a wedge; (b) applying varnished cloth insulation; (c) applying linen-finished tape

from the coil face, a pressboard strip 0.3 to 0.5 mm thick is inserted between the turns with damaged insulation.

At the place where the interturn insulation has been renewed, the coil is wrapped half-lap with a linen-finished tape. This operation should be carried out very carefully in order not to damage the insulation of other turns. The sequence of the renewal of damaged interturn insulation is illustrated in Fig. 5.3.

During inspection, it is necessary to evaluate the mechanical strength and degree of ageing of the interturn insulation. Unfortunately, at present there is no accurate method for such an evaluation. In practice, the insulation is considered to be good if it is elastic, has a light colour, and neither breaks nor cracks when being bent at 90°. The insulation is considered to be bad if it is fragile, breaks when being bent at 90°, can easily be removed from the conductor, and is dark in colour. A transformer with such an insulation is unreliable.

5.3. Repairing the Core

The repairing of the core begins with checking its cooling ducts for sludge and the surface for hot spots. Signs of hot spots are oxide tints (changes in the normal colour of steel to yellow, violet, blue, grey, etc.) and the presence of the products of decomposition of oil in the form of a black, sintered mass. In dry-type transformers, the ducts are blown through with compressed air, while in oil-immersed transformers, they are washed with a jet of hot transformer oil.

Then the core is checked for the tightness of clamping of the yokes, the quality of insulation of the laminations, the insulation resistance of the clamping studs, the condition of insulation between the yoke clamps and the core steel, and for minor external defects.

The tightness of clamping of the yokes is usually checked with a knife blade. If the clamping is good, the blade cannot pass between laminations when trying to do this by hand. The tightness of clamping is improved by tightening the nuts on the clamping studs. This operation should preferably be carried out with the aid of torque indicator handle wrenches, the required clamping force being indicated in the assembly drawings of the core.

If the core laminations are insulated with paper, a piece of it at a suitable place (usually at an extending corner of the centre stack) is removed with a knife and checked for colour and mechanical strength. If the paper has a light colour and does not break when being bent at 90°, the condition of the insulation is good. If the paper is brown or dark-brown in colour and breaks when being bent at 90°,

but its structure remains solid, such an insulation is concidered to be satisfactory. A very dark colour of the paper and its easy destruction when being rubbed between fingers, indicate that the insulation of the core laminations is in a bad condition. Varnish insulation is quite stable and does not require special checking.

The insulation resistance of the top and bottom yoke clamping studs is measured by means of a megohmmeter.

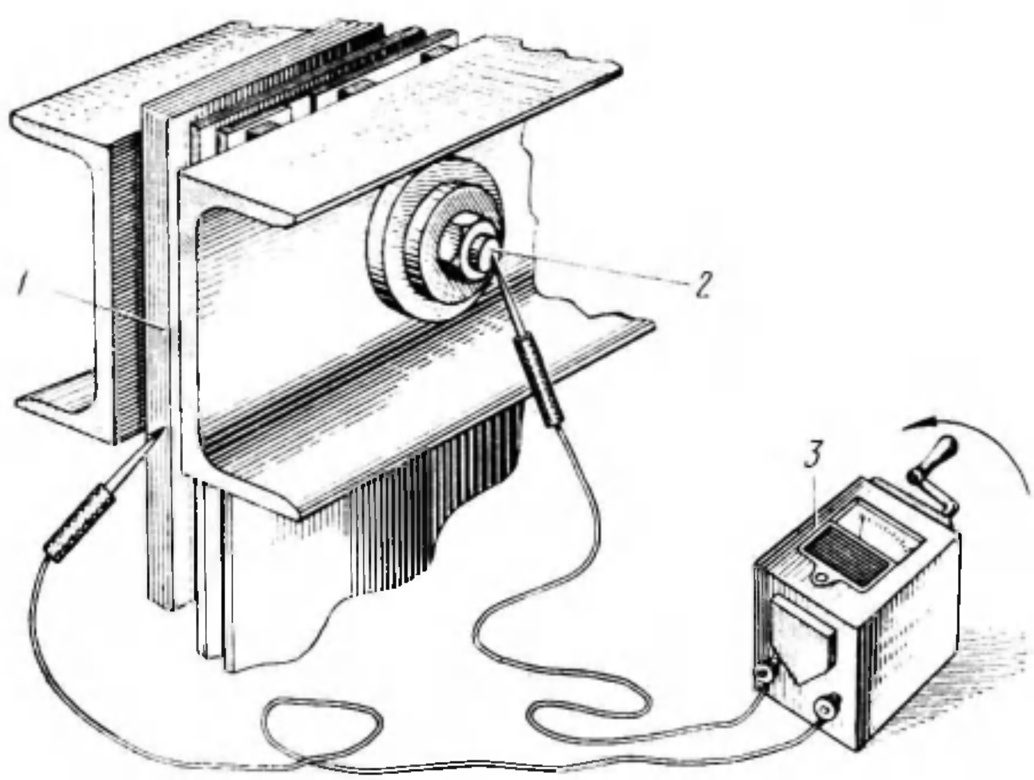


Fig. 5.4. Measuring the insulation resistance of a core clamping stud

1—core steel; 2—clamping stud; 3—megohmmeter

One probe of the instrument is pressed against the core steel, while the other is pressed by turns against each clamping stud, as is shown in Fig. 5.4. The magnitudes of the insulation resistance of the clamping studs and the method of its measurement are given in Sec. 8.2. If the insulation resistance of one or several clamping studs is substantially lower than that of others, or is equal to zero, these studs are undone with a socket or a double-ended wrench and removed together with their insulating paper-base laminate tubes from the holes in the yoke and inspected. If a stud and its insulating tube show signs of overheating (charring, oxide tints, fused spots) and shorted laminations are detected when inspec-

ting the yoke holes with a portable lamp, the yoke is then disassembled to eliminate the fault and if necessary, its laminations are re-insulated. Faulty clamping studs and their paper-base laminate tubes are replaced by new ones.

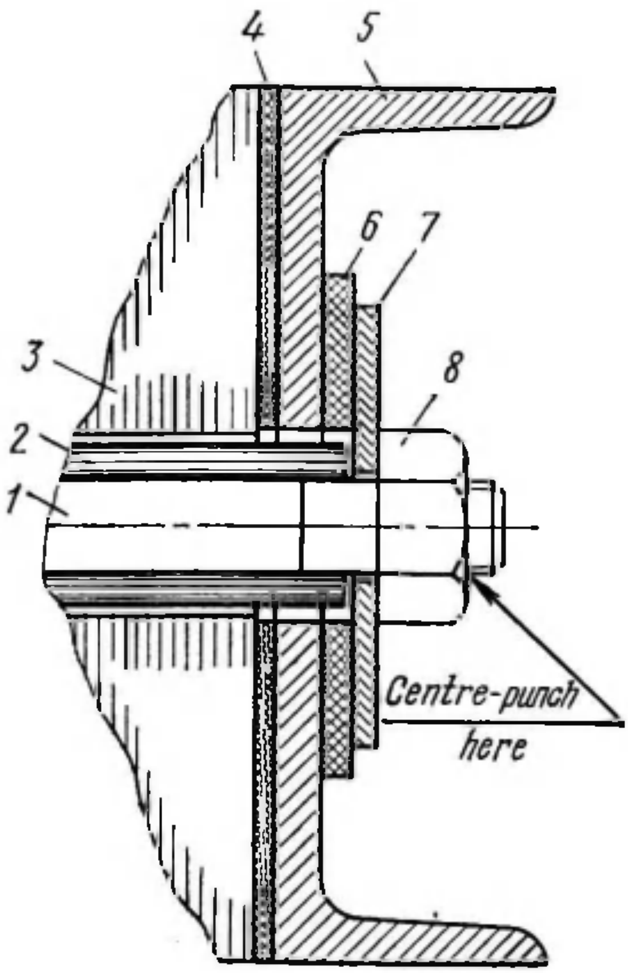


Fig. 5.5. Insulation of a yoke clamping stud

1—clamping stud; *2*—paper-base laminate tube; *3*—yoke laminations; *4*—pressboard strip; *5*—yoke clamp; *6*—pressboard washer; *7*—steel washer; *8*—nut

Before installing the clamping studs in place, the holes in the yoke are carefully inspected and cleaned. If there are bent laminations or sintered lamination stacks, the yoke is disassembled and repaired. After the studs have been made complete with insulating tubes and pressboard and steel washers, they are inserted into the holes in the yoke, nuts are run onto them, and the yoke is clamped by tightening the nuts uniformly on both sides. When doing this, one should see to it that the studs do not rotate in the holes and extend equally on each side of the yoke. The insulating tube *2* of the stud (Fig. 5.5) must not abut against the steel washer *7* when the yoke is in the clamped state, but at the same time, it must overlap the wall of the yoke clamp *5*. Whenever necessary, the tube is shortened so as to ensure that the clearance between its end and the steel washer does not exceed 1.5 to 2 mm when the yoke is tightly clamped.

Prior to the final clamping of the yoke, the earthing strip on the LV lead side is separated from the yoke clamp and the insulation resistance of the yoke clamps relative to the core steel is measured with a megohmmeter. In this way a check is made on the insulation quality and proper placement of the pressboard strips installed between the yoke steel and clamps. For this purpose, one probe of the megohmmeter is pressed against the yoke clamp and the other, against

one of the yoke stacks. At that time the yoke clamps must be tightly pressed against the yokes. If the quality of insulation is good, the earthing strip is re-fitted and the nuts on the clamping studs are tightened home and then centre-punched to prevent them from working loose. The centre-punching consists in that the point of a centre punch is placed between a nut and a stud and their threads are damaged by striking against the punch with a hammer. Nuts are usually centre-punched at three points (Fig. 5.6).

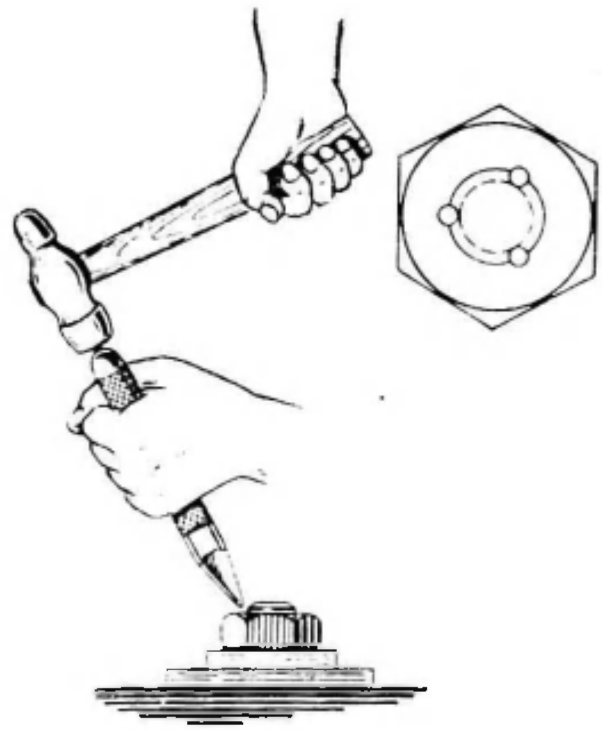


Fig. 5.6. Centre-punching a unit

The finally clamped yokes are checked for the clamping tightness, the insulation resistance of the clamping studs is measured once more, and the earthing circuit of the core is checked for safety. The earthing circuit is checked by means of a megohmmeter. One probe of the instrument is pressed against the core steel and the other, against a yoke clamp. If the circuit is safe, the instrument will read zero. The earthing strips must be held firmly between the yoke laminations and clamp, and must not yield when trying to withdraw them, unless the yoke is unclamped.

When inspecting core-coil units whose cores are clamped without the use of through clamping studs, the clamping tightness is improved by tightening up the nuts on the external clamping studs, steel "boxes", or half-ring binding clips, as the case may be. Then, using a megohmmeter, the half-ring binding clips are checked to see whether the quality of their insulation is good and whether they form a short-circuited turn, and the insulation resistance of the lifting plates (arranged along the core limbs) relative to the core steel is measured. The tightening-up is done with long-handled wrenches (preferably of the torque indicator handle type) capable of producing the required clamping force.

5.4. Repairing the Tap-Changers and Leads

Off-Load Tap-Changers

If the fixed and movable contacts in a tap-changer fit loosely, or if the tap connections are bad (loose screw connections, poor soldered, brazed or welded connections), this will cause a local increase in resistance. The flow of current through such a poor contact causes its intensive heating, oxidation and burning. As the process develops, the circuit eventually breaks, giving rise to an electric arc which causes a major breakdown. To avoid this, all the contacts and lead connections of the tap-changer are carefully checked when inspecting the core-coil assembly. The contact pressure is checked in various ways depending on the tap-changer construction, e.g., by applying pressure to the movable-contact segments or rings by hand (the absence of spring action indicates that the pressure springs of the contacts are broken and must be replaced), by using a feeler gauge (for knife-blade contacts), or by measuring the contact resistance.

Special attention is paid to the condition of contact surfaces. If there are signs of pitting or fusion, the tap-changer is replaced. Sometimes, depending on the nature of failure, it is dismantled and repaired. When dismantling the tap-changer, each lead must be marked with a tab in order not to confuse the lead connections during reassembly.

When the tap-changer operates in oil for a long period of time, its contact surfaces become covered with a thin deposit in the form of a yellowish film. This film increases the resistance across the contacts, which causes their overheating and burning. To remove the deposit, the contact surfaces are carefully wiped with a piece of clean cloth wetted with acetone or gasoline. The rest of the tap-changer is washed with clean transformer oil. All the nuts holding the leads to the fixed contacts of the tap-changer are tightened up. After that, the distances between the flexible portions of the leads are checked, for the leads may be displaced during tightening-up and may come too close to one another. Then the fastenings securing the tap-changer to the yoke clamps are tightened up and finally, the operation of the tap-changer

is checked by shifting it from position to position (the tap-changer must shift with a snap).

When inspecting tap-changers whose operating mechanism is fastened to the tank cover, the rubber sealing gasket under the switch flange is replaced and then the flange is re-fitted by uniformly driving in the fastening bolts in turn, so as to ensure that the flange will not be slanted and the gasket will be shrunk uniformly over its entire circumference. The proper position of the movable contacts relative to the fixed ones, as well as that of the operating knob, is ensured by manipulating the indexing ring *14* (see Fig. 3.32*b*).

On-Load Tap-Changers

The repair work on these tap-changers involves cleaning, washing and wiping of the internal and external surfaces of their units and components, checking of the contact surfaces of the selector switches, divertor switches, and drive-control switches (controllers, relays, limit switches), and adjusting or replacing of the driving gear components. Pitted contacts are carefully ground and then checked for fit (the cause of pitting should be revealed and eliminated). Ceramic contacts are neither ground nor filed, but replaced by new ones, if burnt out to a depth of 7 mm or more.

The main cause of the pitting of selector and d vertor switch contacts (the main contacts in the contactor-type switches) is the maladjustment of the operating mechanism due to excessive backlashes resulting from wear of components and loosening of the joints between the various shafts of the mechanism. The backlashes are eliminated by tightening up the joints and replacing badly worn components.

After it has been repaired, re-assembled, and wiped clean, the tap-changer is checked for the proper joining of all the components of the operating mechanism and contact systems. When re-assembling and adjusting the tap-changer, one should follow the match-marks punched on the mating parts during their assembly at the manufacturing plant.

During repair, special attention should be paid to the check on the proper connection of the leads to the tap-changer contacts, for a wrong connection may cause a failure of the tap-changer and thus put the transformer out of

operation. To exclude any possibility of mistakes in the lead connections, a circle diagram is plotted which shows the operating sequence of the tap-changer contacts.

After repair, the operation of the tap-changer is checked by shifting it several times from position to position throughout the entire voltage-control range in forward and reverse directions both by hand and by means of the motor driving gear. Then the contact pressure in the selector and divertor switches is checked with a dynamometer against the data given in their specifications.

The oil in the divertor-switch tank is usually replaced. According to the relevant instructions, it must be replaced as soon as its breakdown voltage falls down to 22 kV. Other characteristics of the oil in the divertor-switch tank are not specified.

The Leads

When inspecting the leads, special attention is paid to their insulation at places where they are connected to one another and to the windings. The signs of bad connection of

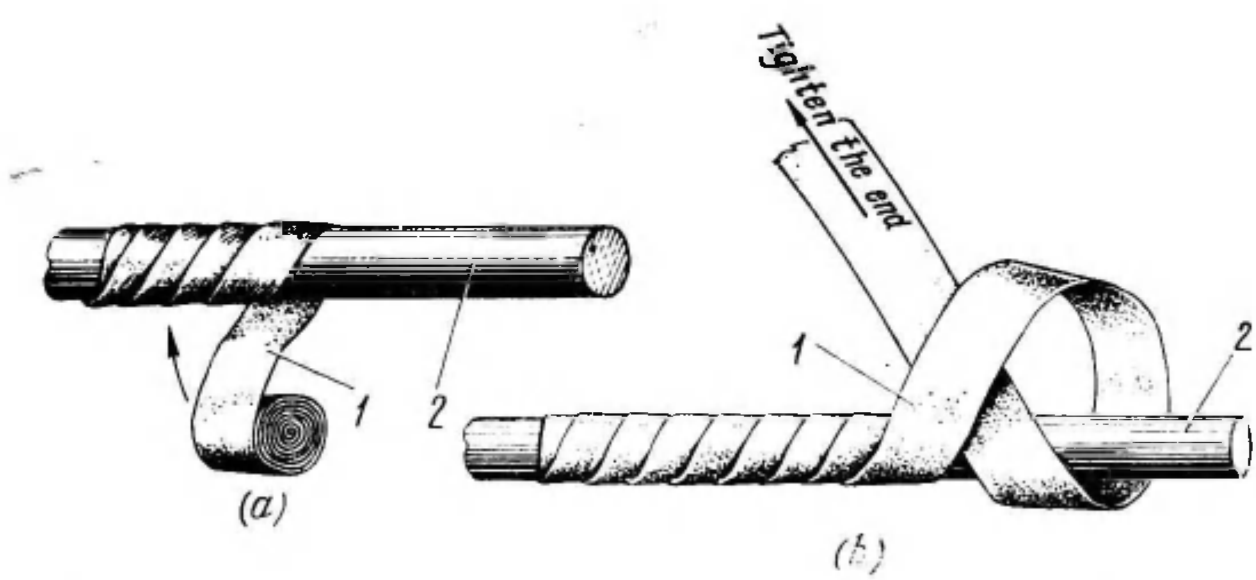


Fig. 5.7. Insulating a conductor with a tape wrapped half-lap

(a) applying the tape; (b) terminating the tape ends; 1—tape; 2—conductor

leads operating in oil are the darkening of their insulation and the deposition of a black, sintered mass on their surface.

The detected faulty connections are re-soldered. Usually, in transformers that were in service for as long as 15 years,

the cotton insulation placed over the main insulation of the leads is worthless. Therefore, it is replaced by a single layer of linen-finished tape wrapped half-lap. This method of insulation (Fig. 5.7) consists in that the lead is taped in such a manner as to ensure that each subsequent turn of the tape overlaps the preceding one by one half of the tape width. The start of the tape is made fast by putting the second turn concentrically around the first, and its finish is passed under the last turn (it being loosened beforehand) and then tightened and cut off.

Then the fastenings of the entire lead support structure are tightened up. Care should be taken when tightening up wooden nuts, for their threads may be stripped, or the nuts themselves may break, should an excessive force be applied to the wrench. Most reliable is the method of fixing the leads between the supporting cleats by means of fabric-base laminate studs and plastic nuts.

If necessary, strips of cable paper or pressboard are wound in concentric layers around the leads at places where they pass between the cleats.

5.5. Repairing the Terminal Bushings

During minor repair (inspection), the terminal bushings are dismantled from the tank cover, carefully inspected, and checked for breakages and cracks in the porcelain insulators, the condition of the sealing gaskets, and the safety of the threads of the terminals and nuts. Damaged porcelain insulators are replaced, while the current-carrying parts and fasteners are mended, if necessary. After cleaning and washing, the bushings are re-assembled, the rubber sealing components being, as a rule, replaced by new ones.

At present, a large number of transformers equipped with permanent (nondetachable) bushings are still in service. Such bushings have frequently to be repaired, since their replacement by detachable (knock-down) bushings involves a modification of the tank cover and the manufacture of a number of fasteners. If an oil leakage through the sealing cement is detected when inspecting a terminal bushing, the latter is either replaced or re-cemented.

To remove old cement and dismantle the flange when it is necessary to renew the seal, the bushing is placed in an oven and heated to a temperature of 400 to 500°C. In one to two hours, the cement crumbles out, so the flange can be easily detached from the insulator.

The bushing is assembled for re-cementing as follows (Fig. 5.8). The bushing cap *1* with the terminal *6* screwed in

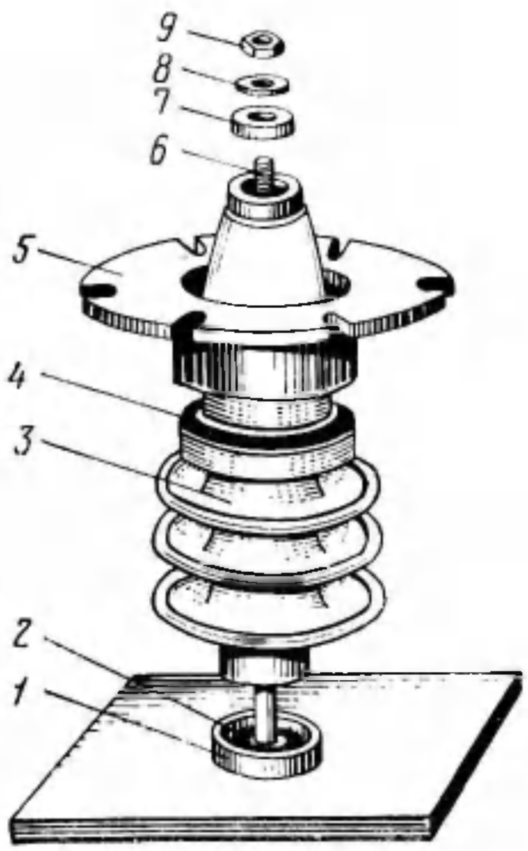


Fig. 5.8. Assembling a terminal bushing for re-cementing

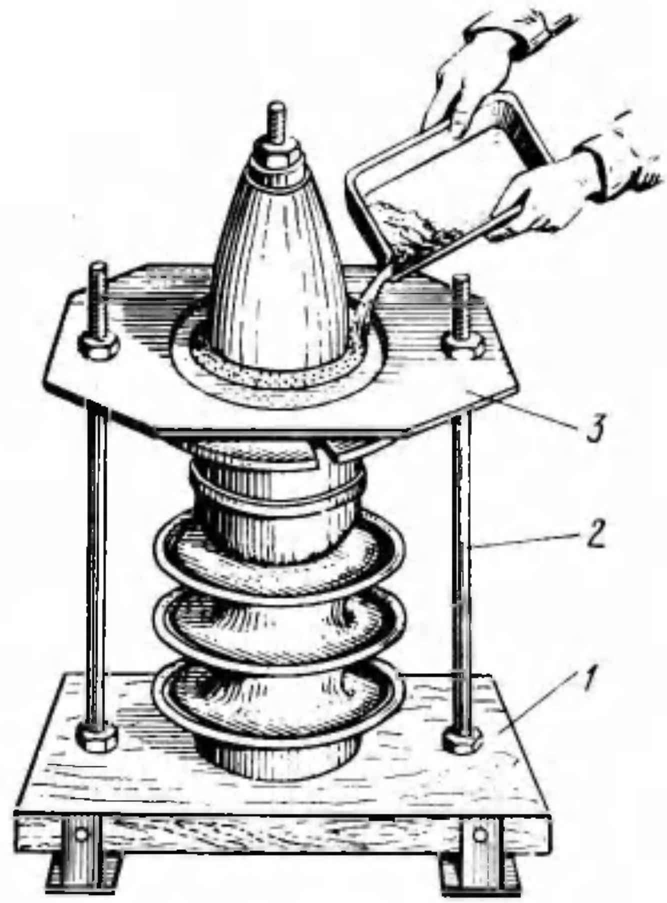


Fig. 5.9. Installing a terminal bushing in a fixture and pouring cement

and soldered to it, is placed in a vertical position. The annular rubber sealing gasket *2* is placed in the cap and the porcelain insulator *3* is mounted on the terminal. Then the rubber gasket *4* and the flange *5* are mounted on the insulator. This gasket is intended to protect cement against decomposition in service and also, to prevent liquid cement from entering the bushing during pouring. After that, the paper-base laminate washer *7* and the steel washer *8* are fitted onto the end of the terminal, and the nut *9* is run onto it and tightened home. When doing this, one should make sure that the terminal is at the centre of the hole in the insulator.

The bushing is re-cemented in a fixture shown in Fig. 5.9, or in a similar device. The porcelain insulator and flange of the bushing are tightly clamped between plates *1* and *3* by means of clamping studs *2* fitted with nuts. When clamping the bushing, one should check that the gaps between the cap and the insulator and between the flange and the insulator are uniform over the entire circumference of the bushing. After that, cement is prepared in a ceramic or metal pan and poured into these gaps.

The bushing is held immovable in the fixture until the cement is hardened completely. Then the top plate is removed, the bushing is cleaned from cement runs, and the surface

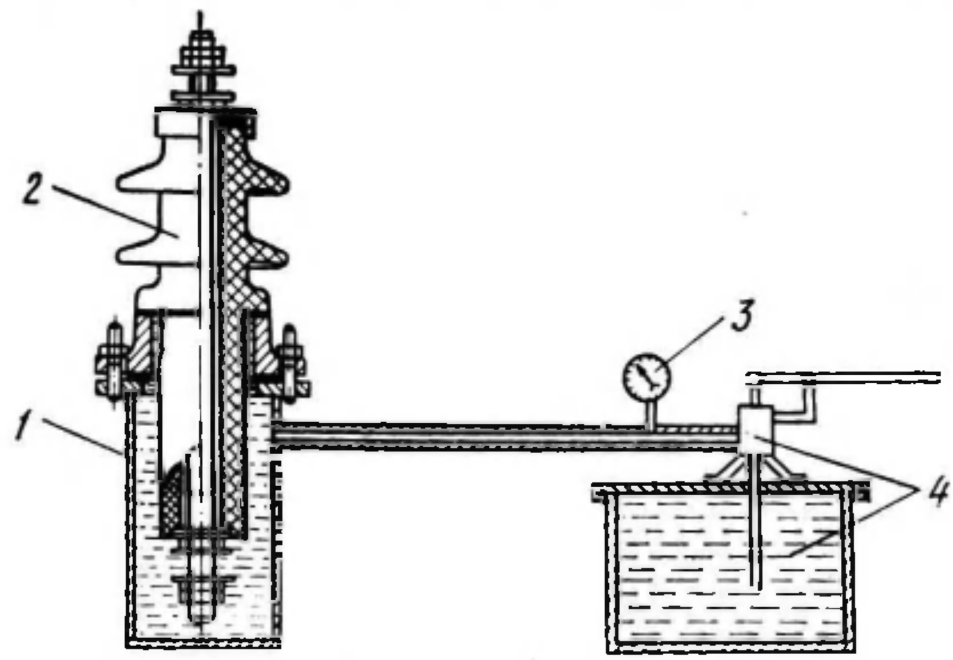


Fig. 5.10. Testing a terminal bushing for leak tightness

1—tank with hot transformer oil; *2*—bushing under test; *3*—pressure gauge; *4*—hydraulic press

of cement is coated with enamel No. 1201 or 624C. Since yellow lead is very expensive, yellow lead-glycerine cement is used only in certain cases. When repairing terminal bushings on a mass scale at a specialized plant, use is made of magnesite cement. In this case, the bushings after cementing are held at a room temperature for 18 to 20 hours and the surface of magnesite cement is coated with varnish.

After re-cementing, the bushings are checked for leak tightness, subjected to electrical tests at a laboratory, and then mounted back on the transformer.

The leak tightness of the bushings is checked by subjecting them for 1 hour to an oil pressure of (1.5 to 2) $\times$ 10^5 Pa

(gauge) at a temperature of 60 to 70°C. To pressurize the bushings, use is made of a hydraulic press *4* (Fig. 5.10) similar to that employed to pressurize pipelines. The soldered and welded components of the terminal bushings are also checked for leak tightness by pressurizing, soapsuds being used to detect leaks.

Damaged threads in nuts and on terminals are mended with the aid of taps and dies.

All the repaired bushings are made complete with washers and nuts. There must be three nuts on each end of the terminal. The third, last (lock) nut serves to prevent the first two from working loose.

5.6. Repairing the Tank Cover and Installing the Terminal Bushings and Other Fittings on the Cover

In Size I through III transformers, the terminal bushings, tap-changers, valves, and other fittings are fastened with studs. Therefore, after cleaning and wiping the cover, all studs are inspected and mended, if necessary.

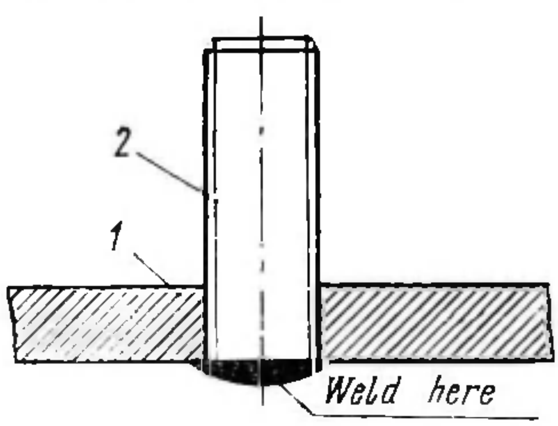


Fig. 5.11. Installing a stud on the tank cover

1—tank cover; *2*—stud

A bent stud can be straightened by screwing a nut onto its end and tapping a hammer against this nut. Studs with damaged threads or fractures are replaced by new ones. To install a new stud, a hole is drilled in the cover and then tapped, the stud *2* (Fig. 5.11) is screwed into the hole, and its end on the back of the cover is arc-welded all around with an oil-tight seam, as shown in the figure.

The lifting rods (Fig. 5.12) are sealed and fastened most carefully, because weak tightening of their nuts and inadequate sealing with asbestos packing result in oil leakage. In minor repairs, the cover *5* is usually not dismantled, therefore the lifting rods are sealed in turn in the following way.

First, the distance between the top yoke clamp and the cover is measured with a rule, a strip of wood being frequently used for this purpose. Then the lifting eye *1* and

the top nut *2* are run off the rod *8* and the top washer *3* is removed. The bottom nut *7* together with washer *6* is run down 30 to 40 mm relative to its normal position, and the old packing *4* is removed with a steel hook.

After that, the nuts that hold the bottom end of the lifting rod to the yoke clamp are tightened up and locked. Where square lock washers are used instead of lock nuts, the washer must be undone with a chisel before tightening up the nuts on the rod, and after the nuts have been tightened up, one of the washer's corners must be bent on the yoke clamp flange and another, on a face of the nut. When doing this, one should make sure that the rod does not rotate and is not displaced relative to the yoke clamp and that the corners of the lock washer are safe and will not break and fall into the transformer tank.

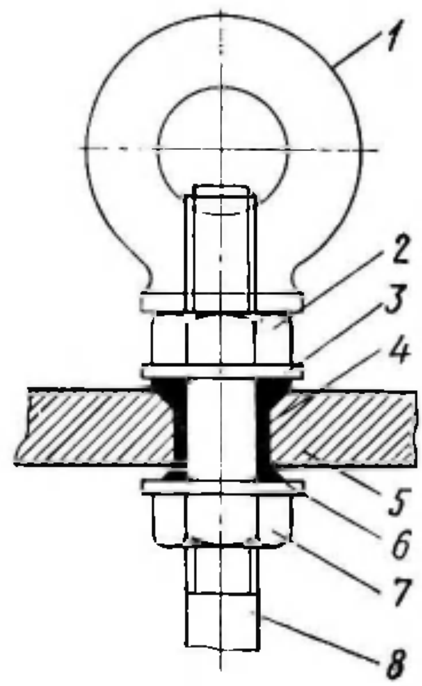


Fig. 5.12. Sealing of a lifting rod

The lifting rods are sealed with a special asbestos packing or with asbestos cord. Where asbestos cord is used, it is untwisted into separate strands, the strands are impregnated with phenolic varnish, held in air for 15 to 20 minutes and then wound around the threads of the rod on both sides of the cover *5* in the same direction as the nuts run during tightening, the thickness of the wound asbestos being such as to ensure that it will fill up the gap between the rod and the cover and will be tightly packed between them upon tightening the nuts.

The washer *3* is then put in place and the nuts *2* and *7* are tightened home, the distance between the cover and the yoke clamp being checked. When tightening the nuts, the asbestos packing extending outside is knocked back under the washers with a chisel and its excess is cut off. Finally, the nut *7* is centre-punched to prevent it from working loose.

Next, new sealing gaskets are made for the fittings that were dismantled from the cover, and the fittings are installed in place.

The gaskets are made from oil-resistant rubber by means of special devices or manually. The inner diameter of a

gasket must be 8 to 10 mm greater than that of the mating flange in order to ensure that during tightening the gasket will not be forced from under the cover, otherwise the exposed part of the gasket will rapidly be destroyed by hot oil.

Prior to mounting, the gaskets are coated on one side with rubber cement, or cement No. 88, held in air for 10 to 15 minutes, and then placed with the coated side down on the surface of the cover, the latter being wiped dry preliminarily. For the gaskets to have uniform shrinkage and to ensure tight fit, the nuts should be tightened uniformly over the entire circumference of the flanges.

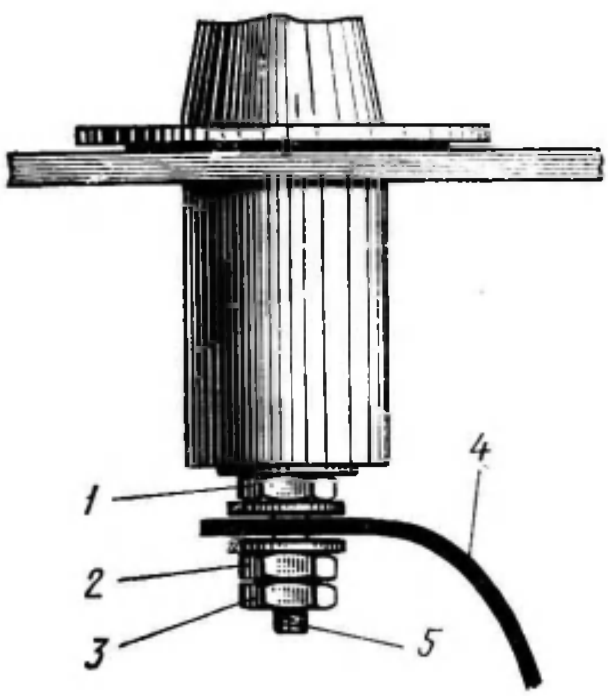


Fig. 5.13. Fixing a flexible connector to a terminal bushing

Particular attention should be paid to the mounting and fastening of the terminal bushings. Their flanges must have no slant relative to the cover and must be clamped uniformly. This is achieved by tightening up the clamping nuts in a crisscross fashion. When connecting a flexible connector *4* (Fig. 5.13) to a bushing, first the nut *1* (the first from the bushing) is tightened and then the flexible connector or its terminal is fitted on the terminal *5* between washers. After that, the nut *2* is screwed home and finally, the lock nut *3* is tightened as far as it will go, the nut *2* being prevented from rotation by holding it with a wrench. An excessive tightening of the nuts may cause damage to their threads, while their weak tightening may result in a poor contact. Therefore, the nuts are tightened by means of standard wrenches without using additional levers.

5.7. Repairing the Tank, Oil Conservator, and Other Fittings Installed on the Tank Cover

The **tank** must be completely repaired by the end of the inspection of the core-coil assembly. When repairing the tank, it is emptied of oil, all the fittings installed on its

walls are dismantled, and its internal and external surfaces are wiped clean. If oil leaks were detected when inspecting the tank, the cracked or otherwise damaged welds are mended by arc welding. When performing welding operations, the tank walls must be wiped dry, fire preventing rules being observed strictly. Old sealing gaskets are removed from the flange of the top tank frame, as well as from the flanges of the dismantled fittings, and the flange surfaces are carefully cleaned.

Transformer tanks are fitted with valves of the screw-down type. The valves are repaired as follows. First, the bolts that hold the valve to the flange on the tank wall are undone and the valve is dismantled. Then the valve is disassembled, its components are cleaned and washed, and its gland packing is replaced. After that, the valve is re-assembled and tested for leak tightness. Should it prove to be leaky, the valve and its seat are lapped in. Then an annular rubber gasket is cut out to fit the flange, and the valve is mounted back in place. After that, the internal surfaces of the tank are finally wiped and washed with clean transformer oil, dirty oil is drained off through the drain hole in the tank bottom, and the drain plug is re-fitted, asbestos cord impregnated with phenolic varnish being used to seal it.

Then a new sealing gasket is placed on the flange of the top frame of the tank. To prevent the gasket from being forced inside the tank when tightening the nuts on the cover, various methods may be used. Fig. 5.14*a* illustrates a method whereby a steel rod *1* having a diameter of 4 to 5 mm is welded to the top tank frame *5* over its entire periphery. A similar method is shown in Fig. 5.14*b*, but here the part of the steel rod is played by the tank wall extending above the frame surface. In some cases, a wide gasket made of roll rubber is placed as shown in Fig. 5.14*c*.

When making gaskets of strip rubber, the joints between separate strips are cemented and arranged so as to ensure that they are between the holes in the tank frame. Fig. 5.15 illustrates one of the most widespread methods of butting the gasket strips, the length of the joint as a function of the gasket thickness being indicated.

When inspecting the **oil conservator**, in the first place attention is paid to the condition of its internal surface.

During operation of the transformer, the upper portion of this surface is in a prolonged contact with warm, and at times damp air and therefore, is subjected to corrosion. If corrosion is negligible, the oil conservator is washed and rinsed several times with clean oil, but if it is heavy,

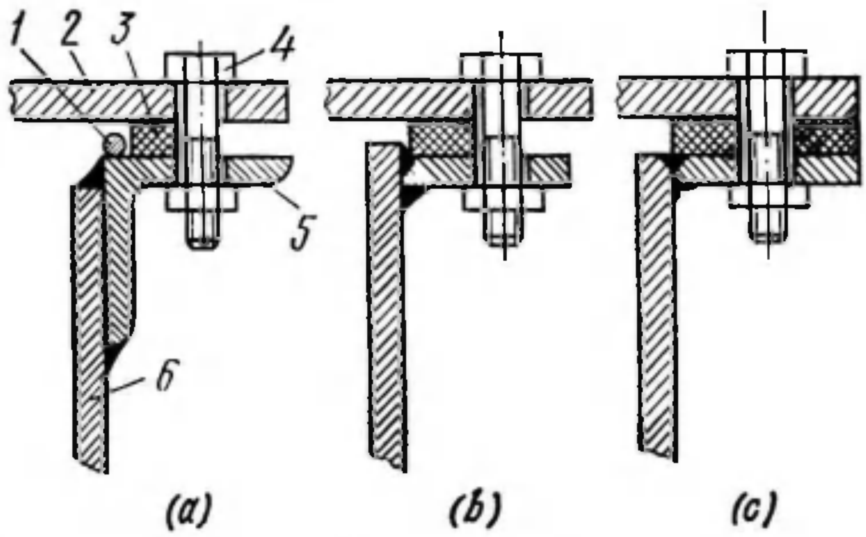


Fig. 5.14. Methods of installing the sealing gasket under the tank cover of a transformer, which prevent the gasket from being forced inside the tank

(*a*) welding a steel rod to the top tank frame; (*b*) welding the top frame to the protruding tank walls; (*c*) using a wide gasket; *1*—steel rod; *2*—tank cover; *3*—gasket; *4*—bolt holding the cover to the tank; *5*—top tank frame; *6*—tank wall

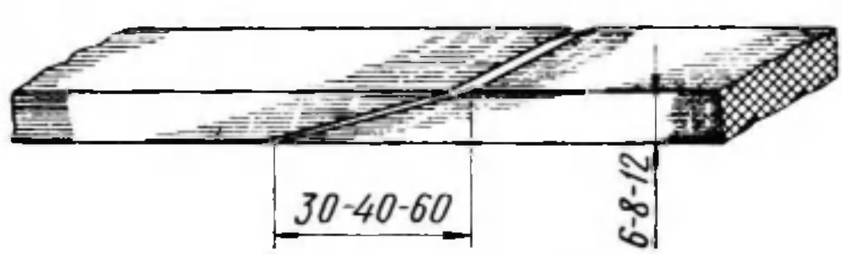


Fig. 5.15. Butting the ends of a gasket

one of the side walls of the conservator is cut out by means of a special device, rust is removed with wire brushes, and the conservator is painted on the inside with the 624C or 1201 enamel. Then the wall is welded in place. For convenience in repairing and painting, the oil conservators of all newly manufactured transformers have special openings in their side walls.

After that, all the plugs, the sump, and the oil gauge are inspected. The rubber gaskets and gland packings of the

oil gauge are replaced by new ones, all the parts are cleaned and washed with kerosene.

The sump *8* (see Fig. 3.54) is emptied of dirty oil residues and sludge and washed with clean oil, the asbestos packing on its drain plug is replaced, and the gauze on the breather pipe passing through the sump is checked for safety.

When inspecting the transformer, its **radiators** (coolers), **explosion-vent tube, breather, thermosiphon filter,** and their

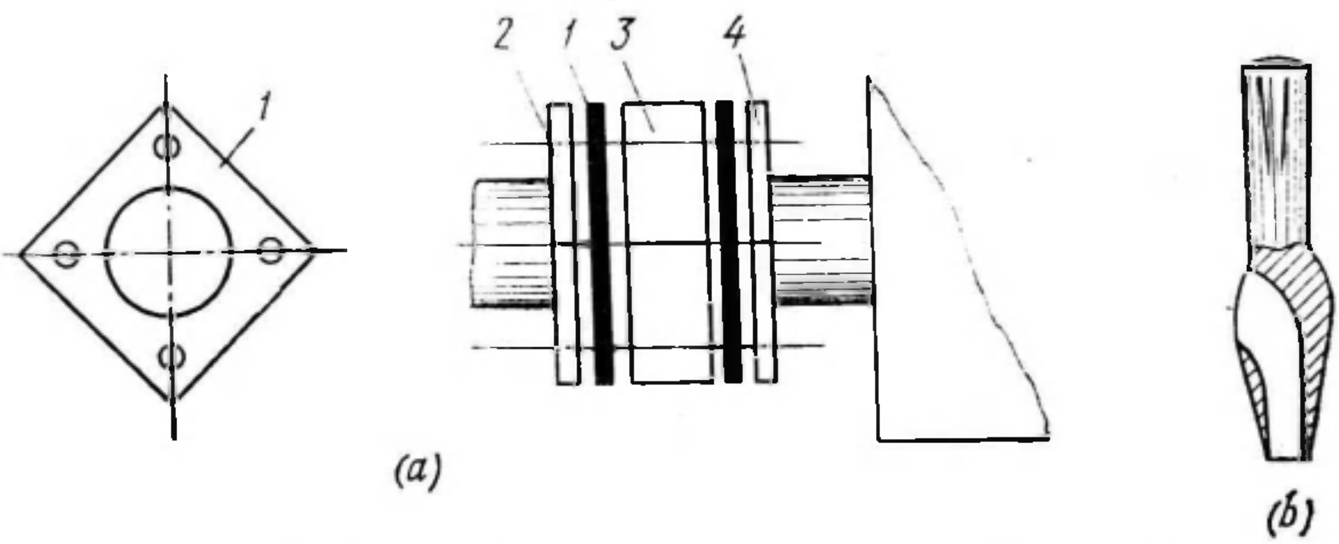


Fig. 5.16. (*a*) Mounting of sealing gaskets on a radiator and (*b*) a steel hollow-punch

valves are repaired simultaneously with the tank. The repair of these fittings involves basically the same operations as those carried out when repairing the tank, i.e., cleaning, washing, painting, testing for leaks, making and replacing sealing gaskets, and replacing the gland packing of valves and asbestos seals on plugs.

The radiators are tested for leaks by pressurizing with a hydraulic press. If leaks are detected, the internal surfaces of the faulty radiator are carefully degreased by steaming and rinsing with hot water. Then the cracks are stopped by arc welding and the radiator is tested for leaks once more. If the radiator passes the repeated test, its connections are closed with blind flanges placed on rubber gaskets, and the radiator is stored in this condition until it is time to mount it on the tank. The radiators that have not shown any signs of leaks from the very first, are put in an inclined position on trestles and carefully washed with hot transformer oil by means of a filter press.

Figure 5.16*a* illustrates the mounting of rubber sealing gaskets on a radiator. Each radiator connection is fitted with two gaskets *1*, one of them being placed between the radiator flange *2* and the radiator valve *3* and the other, between the valve and the flange *4* of the tank connection. The gaskets are cut out to the size of the valve from a sheet of oil-resistant rubber 8 to 10 mm thick. The holes in the gasket are punched by means of a special hollow punch (Fig. 5.16*b*).

When inspecting the thermosiphon filter and breather, silica gel is replaced.

5.8. Tanking the Core-Coil Assembly

After the cover has been repaired and made complete with the terminal bushings and other fittings, and all the leads have been connected, the core-coil assembly is carefully wiped (except for the windings which are only washed with oil) and finally inspected. It is necessary to check that there are no tools, especially knives, screw drivers and wrenches, left on the core-coil unit during repair. Then the insulation resistance of the windings and clamping studs is measured with a megohmmeter. With this the inspection of the core-coil unit and cover is ended, and laboratory personnel carry out preliminary tests.

Should the insulation prove to be moist, the core-coil assembly is dried out, but if the tests show that there are no defects and the insulation is dry, it is prepared for tanking. The unit is slinged, lifted 100 to 200 mm and left suspended to check on the correctness of slinging and the operation of the hoisting mechanism and its brake in particular.

Prior to tanking, the insulation resistance of the clamping studs is measured once more and the yoke and coil-end insulation components are checked for slackness. At the same time, one should check the quality of cleaning, washing, and fastening of all the units and parts, especially of those at the bottom of the core-coil assembly, that can be additionally inspected and cleaned while the assembly is held suspended. The support planks are carefully wiped with clean sweat rags, their fastening to the yoke clamps is checked and if necessary, the fastening nuts are tightened up and centre-punched.

Then the core-coil assembly is lifted with care, without jerking and swaying, and located above the tank. If its position with respect to the tank is correct, the assembly is slowly lowered while being held and directed in such a manner as to ensure that the support planks do not brush against the tank walls.

In transformers of up to 250 kV A, the core-coil assembly is fixed in the tank by means of angles and brackets welded to the tank walls and the yoke clamps, in those ranging from 400 to 1 600 kV A or somewhat more, it is fixed by means of brackets and hooks tied to the yoke clamps and the tank walls, and in those of 2 500 kV A and over, by means of set screws driven in special sockets welded to the tank walls, the free ends of the screws being pressed against thrust plates mounted on the yoke clamps.

If the core-coil assembly is connected to the tank cover by the lifting rods, it is lowered into the tank until the cover is 50 to 100 mm from the top tank frame. Then several round steel aligning bars are passed through the bolt holes in the cover and frame, and the core-coil unit is lowered further until it rests on the tank bottom and the cover closely fits the sealing gasket on the tank frame, the cover together with the core-coil unit being directed by the aligning bars. When doing this, it is necessary to see to it that the sealing gasket is not displaced. After that, bolts are inserted into the holes and nuts are run onto them and then tightened uniformly as far as they will go by making several rounds over the entire periphery of the cover.

Where there are joints in the gasket, the nuts are tightened while going toward the joint from both sides. This ensures tighter butting of the joined ends of the gasket. Bolts and nuts with stripped threads or rounded corners are replaced by new ones, while those with slightly damaged threads are mended.

After tanking the core-coil assembly and bolting the tank cover, the tank is filled with dry, clean oil slightly above the level of the top yoke by means of a centrifugal oil separator (purifier) or filter press. The oil temperature must not be lower than 10°C. To bleed air out of the tank when filling it with oil, one of the openings in the cover must be kept open, but it must be guarded so as to exclude any possibility

of foreign objects getting into the tank inadvertently. Transformers having no oil conservator are filled with oil up to the level indicated by an appropriate line marked on the tank near the oil gauge.

5.9. Mounting the Oil Conservator, Buchholz Relay, and Other Fittings. Testing the Transformer for Leak Tightness

Mounting the Oil Conservator, Buchholz Relay, and Other Fittings

Next come the mounting and fastening of the oil conservator, Buchholz relay, explosion-vent tube, and other fittings. Light fittings are lifted and mounted by hand, while

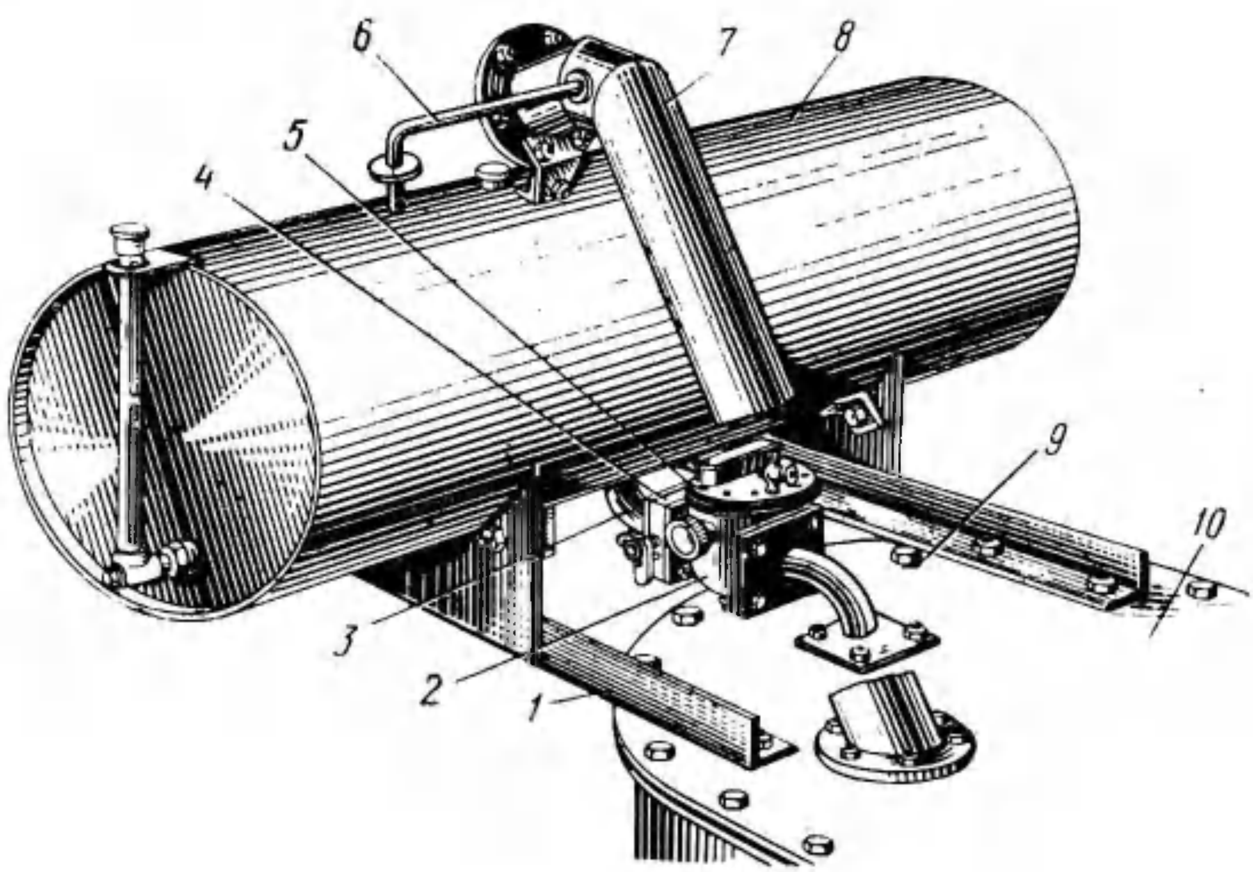


Fig. 5.17. Mounting the oil conservator, Buchholz relay, and explosion-vent tube on a transformer

heavy ones, by means of hoisting mechanisms. All these fittings are installed in the order opposite to that of their dismantling (Fig. 5.17). First, brackets *1* are fastened to the transformer cover *10* and then the oil conservator *8* is lifted and mounted on them. The valve *4* is fixed to the flange *3*

of the conservator connection and the tank connection *9* of the relay is secured to the tank cover, all sealing gaskets being replaced by new ones. After that, the Buchholz relay *2* (preliminarily checked at a laboratory) is installed between the valve and the flange of the tank connection so that the arrow on the top flange *5* of the relay points towards the conservator. When bolting the relay, it is necessary to see to it that the connecting flanges of the relay, the flange on its tank connection, and the surface of the valve are parallel to one another and that the sealing gaskets between them have uniform shrinkage.

To facilitate the installation of the relay, the conservator brackets are only loosely fastened to the tank cover , so that the conservator can be somewhat displaced, if necessary. When installing the relay, one should use a spirit level to make sure that the top flange of the relay is strictly horizontal. Then all the fasteners on the relay connections and on the conservator brackets are tightened home and after that, the explosion-vent tube *7* and pipe *6* connecting it to the conservator are mounted and fixed in place, new sealing gaskets being used.

Then the operation of the valve installed between the Buchholz relay and the oil conservator is checked. The temperature-measuring instruments are usually installed on the transformer after they have been tested in a laboratory and after the transformer has been moved to the place of installation.

Testing the Transformer for Leak Tightness

After the transformer has been fully assembled, oil is added to capacity and the transformer is tested for leaks. Additional oil must be of the same batch as that used for filling the tank. To make the tank communicate with the ambient air and let the fittings be filled with oil, it is necessary to open the valve between the Buchholz relay and the oil conservator and remove the top plug of the conservator, as well as all the air-bleed screws and plugs on the terminal bushings, radiators, thermosiphon filter, and other devices where such screws and plugs are provided.

As soon as oil starts leaking through the air-bleed holes, the plugs and screws are driven home while being sealed by wrapping asbestos cord impregnated with phenolic varnish around them under their heads and washers. The cord strands are wound in the direction of the threads and impregnated 15 to 20 minutes before use so as to let the varnish get a little drier and thus prevent it from being squeezed out entirely when tightening the plugs and screws. Should some joints prove to be leaky, the leaks are stopped by tightening up the corresponding fasteners. Oil is added until it reaches the normal level in the conservator, the oil level being followed by watching the oil gauge.

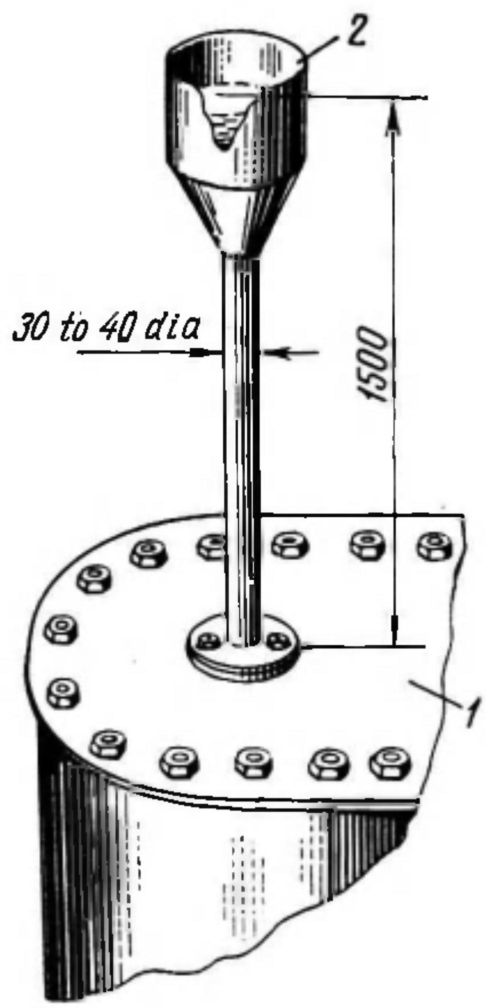


Fig. 5.18. Testing a transformer for leak tightness

1—tank cover; *2*—pipe with funnel

After filling it with oil to capacity and bleeding air from its tank and fittings, the transformer is tested for leak tightness by subjecting it to an excessive oil pressure. For this purpose, a piece of pipe of a certain definite length and 30 to 40 mm in diameter is fitted vertically on the tank cover or on top of the conservator. In the former case, the pipe is mounted over one of the openings in the cover and therefore, its lower end must be provided with a flange, while in the latter case, it is screwed into the filler hole in the conservator, so its lower end must be threaded. The top end of the pipe must be equipped with a funnel (Fig. 5.18).

The pipe is filled with transformer oil and the transformer is kept pressurized for 3 hours. If during this time not a single leaky seal or weld is detected, the transformer is considered to be leak-proof. Should some seals prove to be leaky, the leaks are eliminated either by tightening up the fasteners or by replacing the sealing gaskets.

When testing transformers with plain and tubular tanks, the height of the oil column in the pipe is taken at 1.5 m

from the level of the tank cover or 0.6 m from the uppermost point of the oil conservator, while when testing those having corrugated tanks or radiators, it is lowered down to 0.9 and 0.3 m, respectively. The oil level in the pipe is checked by reference to the marks inscribed on the inner surface of the funnel. Transformers are sometimes tested for leak tightness by using a hydraulic press to build up the required pressure. In this case, one should bear in mind that the pressure of 1 m of oil is equal to 0.082×10^5 Pa.

After testing the transformer for leaks, oil is drained off down to the normal level through the bottom tank valve, the operation of the oil gauge being checked simultaneously. If the gauge operates normally, the oil level in its glass drops smoothly, without disruptions and splashes. If there are disruptions and splashes, this means that the top portion of the glass does not communicate with the atmosphere.

Then a sample of oil for a shortened chemical analysis and electric strength test is taken. The sample is taken in 8 to 10 hours after filling the transformer to capacity, i.e., after air has fully escaped from oil.

After the transformer has been fully assembled and tested for leaks, it is painted on the outside with grey enamel Grade ПФ-133, its surface being preliminarily cleaned with care and its terminal bushings and fittings wrapped with paper in order to protect them from paint. Then the transformer is subjected to final electrical tests.

Review Questions

1. What are the main operations carried out when inspecting the core-coil assembly and the tap-changer of a transformer?
2. What operations are carried out when inspecting the core?
3. Describe the main operations in inspecting the terminal bushings and other fittings of the transformer.
4. How is the core-coil assembly tanked and covered with oil?

CHAPTER SIX

Major Transformer Repair (Overhaul)

Major repair of the transformer involves complete or partial replacement of the windings and major insulation, repair of the core with complete or partial re-insulation of laminations, modernization or replacement of individual devices, cooling system, tap-changer, etc.

During major repair, the core-coil unit has to be disassembled completely. Before disassembling the core-coil unit, the transformer is knocked down in the same sequence as in the case of inspection: oil is drained off completely, the terminal bushings, explosion-vent tube, Buchholz relay, oil conservator, thermosiphon filter, and coolers are dismantled, the tank cover is unfastened, and the core-coil assembly is slinged and withdrawn from the tank. If the tank cover is mechanically connected to the core-coil unit, all the fittings installed on the cover are dismantled and the cover is removed from the lifting rods. If the tank is of the bottom-split type, the tank is removed from its bottom. Then the top yoke is unbladed, the windings are removed from the core limbs, and their insulation is knocked down. If it is necessary to re-insulate the core laminations, the entire core is disassembled.

After the transformer has been completely disassembled, all the dismantled fittings, units and parts are carefully inspected, repaired, if necessary, or rejected and replaced by new ones, if badly damaged. Then the transformer is re-assembled. This type of repair also involves all the operations that are carried out during medium repair (inspection). The drying out of the core-coil assembly and purification of oil are obligatory. During major repair, use is made of various appliances, platforms and scaffolds, depending on the size of the transformer.

Let us consider the sequence of operations in overhauling Size II and III transformers, starting from the moment the core-coil assembly is withdrawn from the tank. Specific features of overhauling more powerful transformers will be considered separately.

6.1. Dismantling the Tap-Changer, Terminal Bushings, Tank Cover and Leads

The disassembly of the core-coil unit that is connected to the tank cover by the lifting rods begins with disconnecting the regulating and line (main) leads from the tap-changer and terminal bushings. Before disconnecting them, the leads are numbered by slipping identification tags over them. The terminal bushings and the tap-changer may be dismantled either before removing the cover from the core-coil unit or after that. The cover is removed by means of slings fastened to special lifting eyes or lugs provided on the cover. If there are no such lifting arrangements, use is made of temporary eye-bolts secured in the bolt holes in the cover.

Before removing the cover, it is necessary to measure the distance between it and the top yoke. This distance is usually measured at each lifting rod, and the results obtained serve as reference when re-assembling the core-coil unit, for should one fail to install the cover correctly as to its height with respect to the top yoke, either the core-coil unit will hang from the cover and not rest on the tank bottom, or the cover will not reach the top tank frame.

After slinging the cover and tightening the slings so that there is no slack in them, the lifting eyes of the transformer are removed in turn from the lifting rods with a jimmy and then the top nuts are run off the rods with a wrench and the washers are removed. Then slowly, without jerks, the cover is lifted. When doing this, one should see to it that the cover does not brush against the threads on any lifting rod and that it is removed from all the rods at the same time. The cover is lifted 100 to 200 mm above the lifting rods and moved to a specially prepared place. If the terminal bushings and the tap-changer have not been removed before that, the cover is placed on trestles so that these fittings do not touch the floor.

Then the nuts on the flanged joints of the terminal bushings, tap-changer, and other fittings installed on the cover are undone, the fittings are dismantled, inspected in the usual way, and put in their allotted places on a rack. After that, the nuts securing the lifting rods to the top yoke clamps are undone, the rods are removed, made complete with their nuts, washers, and lifting eyes, and put away.

Before dismantling the leads, it is necessary to draw a sketch of their layout and fastening. Then the lead-support cleats are unbolted and put on a rack, the HV- and LV-lead cleats being placed separately. The lead-to-winding connections are stripped of insulation with a knife over a length of 50 to 200 mm, depending on the conductor diameter and insulation thickness, the remaining insulation being tapered toward the connection from both sides.

To disconnect taps of large section, their connections are unsoldered by heating them with electric-brazing tongs equipped with carbon electrodes. So that insulation will not catch fire, the skinned conductors near the place where the tongs are applied are coated with wet, pasty asbestos on both sides of the connection. Connections of light-gauge wires are cut with nippers or lever shears, rather than unsoldered. If the windings or leads are not to be replaced, their connections are cut with a chisel precisely at the place where the conductors butt, so as not to damage their ends. Leads that do not need mending are placed on a rack; damaged leads with fused, burnt or otherwise injured insulation are placed separately.

If all the leads have good insulation and do not need replacement, they are not disassembled completely, but are dismantled together with their wooden support structure. This materially cuts down the amount of work involved in the re-assembly of the transformer.

6.2. Dismantling the Top Yoke Clamps and Unblading the Top Yoke

After removing the leads, the top yoke clamps are unfastened and the yoke is unbladed. This job begins with unclamping the windings and the yoke.

If the windings are clamped by steel pressure rings, the clamping screws are then slackened and the insulating saddles

and steel inserts are removed. Where there are no such rings (Fig. 6.1), the unclamping of the windings begins with undoing the nuts *2* on the vertical tie-rods *5*.

Then the nuts *4* on the clamping studs of the top yoke clamps *3* are first loosened uniformly and then run off the studs.

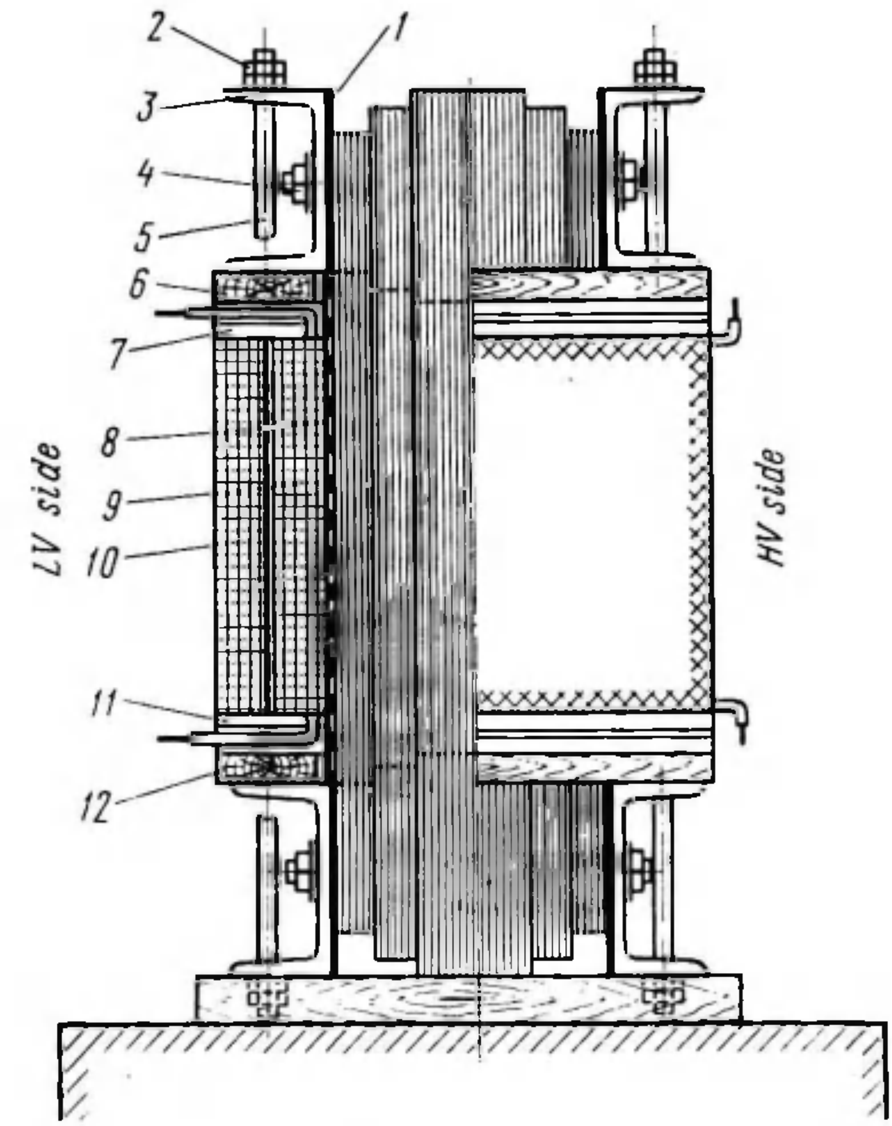


Fig. 6.1. Core-coil unit of a Size II transformer (side view)

The studs together with their paper-base laminate and steel washers and paper-base laminate tubes are removed, inspected, made complete with their tubes, washers, and nuts, and placed on a rack. If a tube cannot be freely withdrawn from its hole in the yoke, it is then knocked out by means of a suitable drift and a hammer.

After that, the top yoke clamps and the pressboard strips *1* that insulate them from the yoke are removed. In small transformers, the clamps are removed by hand, while in large units, they are dismantled by means of hoisting mecha-

nisms with wire-rope slings. In the latter case, the yoke clamps are first slinged and only then are unfastened and removed.

It should be borne in mind that the yoke may spring when being unclamped. Therefore, when removing the top yoke clamps of large transformers, the yoke laminations should be temporarily kept from springing apart by means of U-cramps which are to be inserted between the laminations in a staggered pattern over the entire surface of the yoke after the yoke clamping studs have been broken loose. Moreover, temporary clamping studs with extra-long threads should be inserted into specially provided holes at the ends of the yoke clamps. These studs with nuts run on them will restrict the springing action of the yoke and hold the yoke clamps on the core until they are taken off. Failure to obey this rule may lead to an accident as a result of the yoke clamps being suddenly thrown away by the springy yoke.

The yokes clamped by external, rather than through, clamping studs or by half-ring binding clips are easier to unclamp. In this case, the yoke clamps are slinged and tied together by means of temporary studs, and then the yoke is gradually unclamped until the nuts on its clamping studs or half-ring binding clips are run off. After that, the clamping components and the yoke clamps themselves are removed.

The yoke clamps on HV and LV sides are not interchangeable, therefore they should be marked by inscriptions "HV side" and "LV side" when being dismantled.

The dismantled yoke clamps are usually placed on wooden blocks on the floor.

Then the core earthing strip is removed and the top coil-end insulation *6* is dismantled. If the entire core is to be disassembled, the vertical tie-rods *5* are then removed. During disassembly, all the dismantled parts are carefully inspected and replaced, if badly damaged.

After that, the top yoke is unbladed from both sides (HV and LV) simultaneously, 2 to 3 laminations being removed at a time, depending on their number in a single layer. As the laminations are removed, they are placed in the same sequence one upon another in stacks on a planking or on special portable racks.

6.3. Dismantling the Windings and Insulation. Inspecting the Core

Removing the Windings and Insulation

After unblading the top yoke, the loose ends of the limb laminations protruding above the windings are tightly banded with lengths of surgical tape or soft wire in order to prevent them from interfering with the dismantling of the windings. Then the top yoke insulation *7* (see Fig. 6.1) is removed. If the insulation is proposed to be used again, it is carefully placed on a rack and covered with paper or a piece of tarpaulin. Damaged insulation which is to be replaced or repaired, should be placed separately.

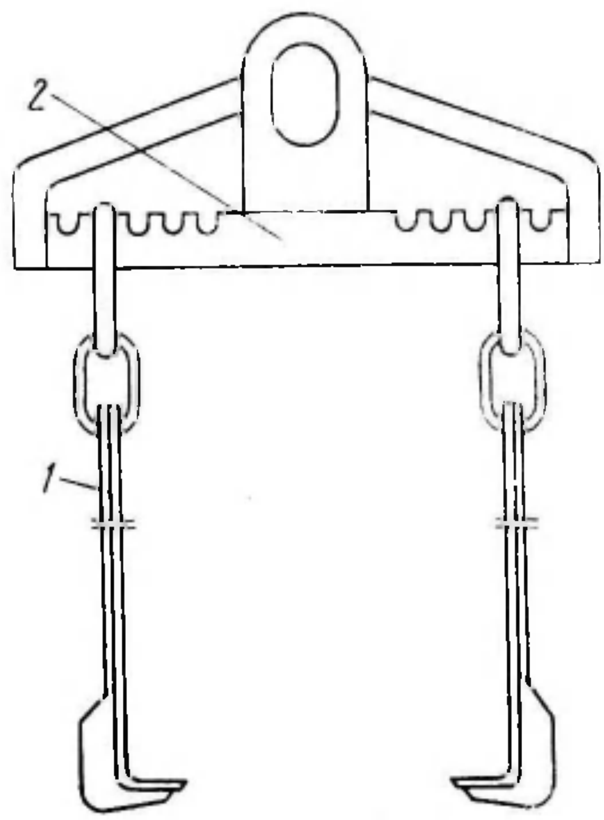


Fig. 6.2. Two-bar spread frame for removing and mounting the windings

Then the dismantling of the windings is started. Should even a single winding of a transformer be damaged, in most cases one will have to dismantle all the windings, because the metal runs and soot, formed as a result of arcing, spread all over the windings and insulation. The dismantled windings are carefully inspected and washed. First the outer (HV) windings *10* are removed, the top ends of the inner (LV) windings *9* being preliminarily bent in such a manner as to ensure that they are vertical and do not touch the outer windings.

The windings of transformers of up to 100 kV A in capacity are dismantled by hand, while those of transformers ranging from 160 to 630 kV A, by means of a hoisting mechanism. Heavy windings are removed by means of a special puller (Fig. 6.2) comprising draw-bars *1* provided with grips at their ends and a two-bar spread frame *2* with a lifting eye at its centre, which serves to hitch the puller on the hook of a hoisting mechanism. Similar devices for removing and

mounting the windings of Size IV through VII transformers use three-bar spread frames with three draw-bars spaced at 120°.

The grips on the draw-bars are brought under the winding and made to engage its support ring at places where there are stacks of interturn spacers, the draw-bars being placed so that they do not touch the adjacent winding or its insulation. To make room for the grips when arranging the draw-bars on the winding, the latter is lifted a little by means of a special appliance the type of a jack, which is put under the winding at several places around its periphery. When doing this, one must be careful not to damage the winding insulation and turns. The winding together with the draw-bars is tightly tied round with a hemp rope in a staggered fashion along its entire height, and then the hook of the hoisting mechanism is brought precisely above the centre of the winding and the spread frame is suspended from it.

The winding is lifted 100 to 150 mm and then it is checked to make sure that the draw-bars are not inclined and the puller is hitched properly. If the winding is fastened properly and the grips on the draw-bars do not catch the inner winding or the insulating cylinder, the winding is removed from the core limb. The dismantled winding is moved aside and lowered on wooden blocks on the floor and then the draw-bars are released. All the HV windings and then the LV windings are dismantled in the same way. Prior to dismantling the LV windings, the draw-bars are re-arranged on the spread bars of the puller to suit the diameter of the windings to be removed.

After all the HV and LV windings have been dismantled in turn from each core limb, the bottom yoke insulation *11* (see Fig. 6.1) and the coil-end insulation *12* are removed. Light windings and their packing components are placed on a rack, while heavy ones are put on a planking on the floor. Then the pressboard cylinders *8* and the beechwood components (round and shaped bars and strips) that pack out the LV windings are taken down. If the windings are replaced because of their insulation being unfit for further operation, the beechwood components are usually replaced as well, the new components being made either after the pattern of the old ones or to drawings.

Inspecting the Core

After dismantling the windings and insulation, the core is inspected. First, it is cleaned of dirt and sludge with rags wetted with some solvent, and then checked for the quality and mechanical strength of the lamination insulation and the condition of insulation between the yoke clamps and the core steel. Paper lamination insulation must be mechanically strong; it must not crumble and get powdered when being rubbed with a finger. The laminations must be entirely covered with insulation. In the case of varnish insulation, the laminations must not stick together and the varnish film must not come off when they are being scratched with a blunt tool. In major repairs, paper lamination insulation is removed and the laminations are varnished.

Then the insulation resistance of the clamping studs of the bottom yoke and core lims is measured, and some of the studs are taken down at random and inspected. If there are no signs of overheating and sintering on the studs and laminations, the insulation of the studs and laminations is strong mechanically, and the holes in the core limbs and yokes are clean, the core is considered to be fit for re-assembly and further operation. Should some minor defects be revealed in the lamination insulation, these are to be eliminated. If the safety of the core is doubtful, it is to be re-assembled, with the top yoke being normally clamped, and subjected to electrical and thermal tests.

6.4. Repairing the Core with Complete Disassembly

Cores with varnish lamination insulation operate fairly reliably over a very long period of time. In practice, there are almost no instances where normally varnished laminations would require re-insulation because of wear of their varnish coating, unless its quality is poor or it is injured by an electric arc or currents flowing through the core as a result of an accidental damage to the transformer. In such cases, the laminations are fused by the arc and burn through at some spots.

One has to re-insulate mainly the paper-insulated laminations in the cores of old transformers that have been ope-

rating for over 20 years. Also, the active core steel has to be re-insulated and repaired in the case of burning off and welding together of the laminations as a result of what is known as "fire in steel". This phenomenon is due to the deterioration of the lamination insulation, leading to the formation of a closed loop (short-circuited turn) in the system of the core and steel structural components of the transformer.

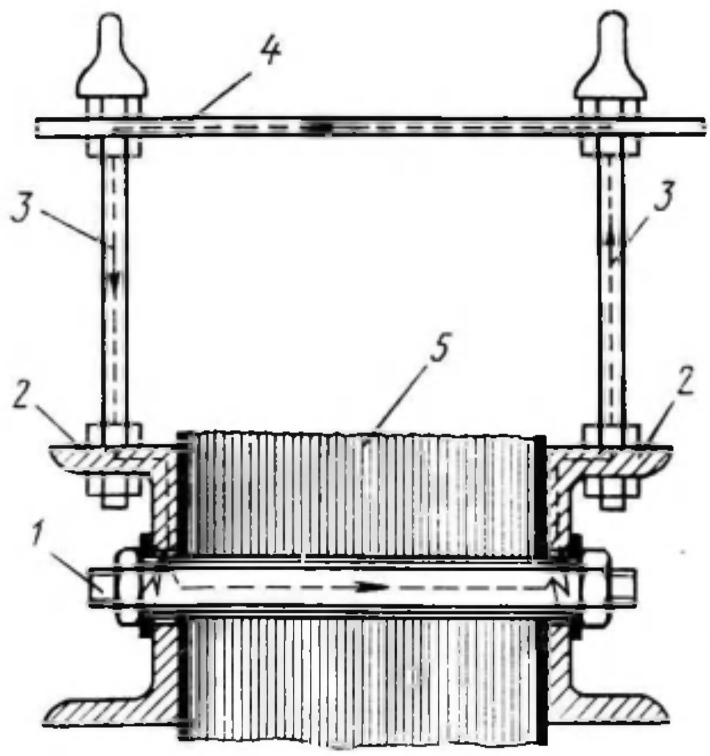


Fig. 6.3. Formation of a short-circuited turn in the case of damaged insulation of a yoke clamping stud

Such a loop, for example, may be formed should insulation of the clamping stud *1* (Fig. 6.3) be damaged at places where it passes through the yoke clamps *2*. In this case, the following short-circuited turn will be formed: the stud— a yoke clamp—a lifting rod *3*—the tank cover *4*—the second lifting rod—the second yoke clamp—the stud. This turn is cut across by the magnetic flux of the upper portion of the top yoke *5*, which induces a heavy current in it. The flow of this current through the loop causes hot spots to form at places where the insulation of the stud is damaged, these in turn causing the insulation and steel to burn.

Closed loops may also be formed on the surface of the core and its holes if the laminations have their edges burred, bent or dented.

The core steel is frequently injured by arcing due to short circuits in the windings.

In most cases, only the top yoke laminations are re-insulated. Each time the top yoke is re-bladed, the core losses increase by 5 to 8%, therefore, the top yoke should not be unbladed if the defect in the transformer can be eliminated without doing this.

The main operations involved in the re-insulation of the laminations of the entire core are as follows.

(a) Disassembling the core.
(b) Cleaning the laminations of old insulation.
(c) Varnishing the laminations and baking the varnish coating.
(d) Re-assembling the core.

All these jobs are fairly laborious and require some preparatory work involving the manufacture of special devices for disassembling and re-assembling the core, removing old insulation from the laminations, varnishing the laminations, baking the varnish coating, etc.

Disassembling the Core

Transformer cores are disassembled and re-assembled in a horizontal position, no matter what the capacity and type of the transformer. Before placing the core in the horizontal position, the vertical tie-rods are removed. The cores of large transformers are placed in the horizontal position, while still assembled, by means of a special, sled-shaped tilter welded from C- or H-iron.

The core *4* (Fig. 6.4) mounted and fixed on the tilter *2* is tilted from vertical into horizontal position by means of a bridge crane equipped with two hooks. The tilter is slinged to the large hook of the crane at point *A* and to the small hook at point *B*, and then it is lifted 5 to 10 cm from the floor and tilted a little. After that, by manipulating the two hooks in concord, the core on the tilter is made horizontal and lowered on the floor in this position.

The entire repair work on the core—its disassembly and re-assembly—is done with the core remaining on the tilter. Once it is repaired, the core is put back in its normal, vertical position by manipulating the tilter in the same way, the sequence of manipulations being reversed (dashed arrows in the figure).

The cores of transformers of up to Size III may be tilted without any tilter. In this case, the large hook of the crane is slinged to the top yoke clamps, while the small one, to the bottom yoke clamps. Then, by manipulating the two hooks in the same way as with the tilter, the core is placed in the desired position. If there is no bridge crane with two hooks, the tilting is done with two cranes.

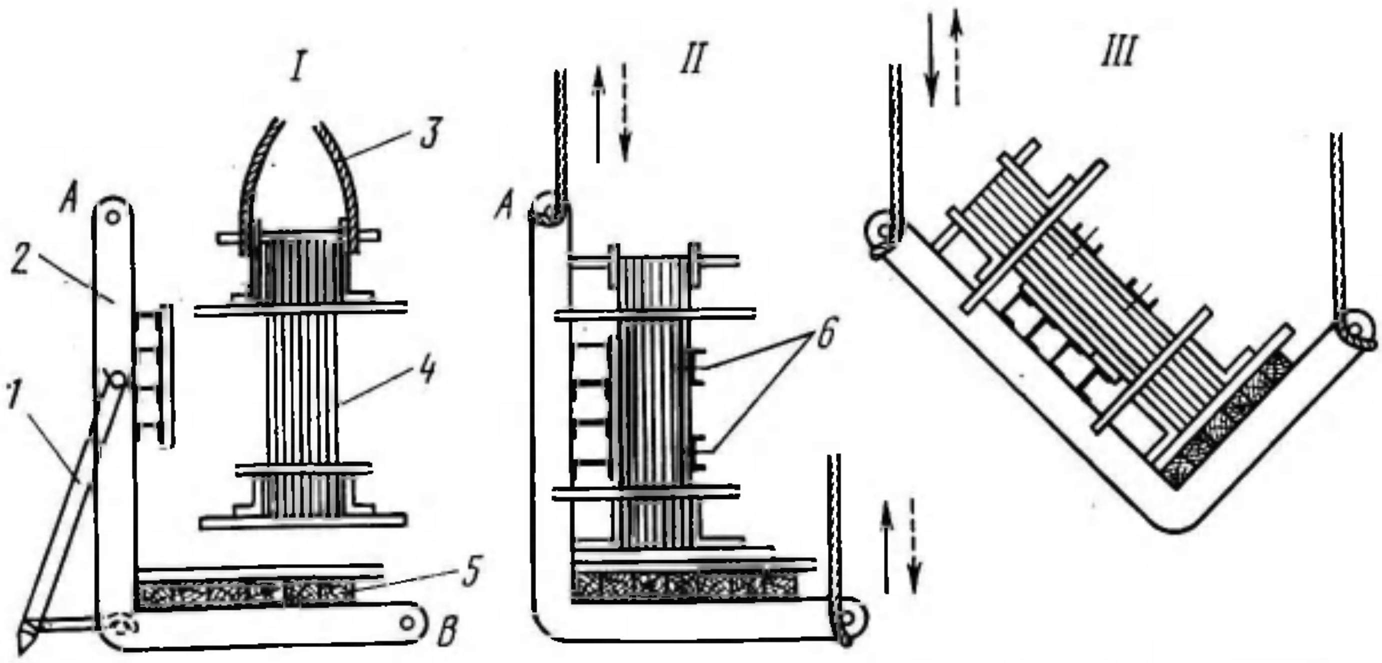


Fig. 6.4. Illustrating the tilting

I—installing the core on the tilter; *II*—fastening the core and slinging the tilter; core; *V*—placing the core for disassembly; *1*—safety rest; *2*—tilter; *3*—slings

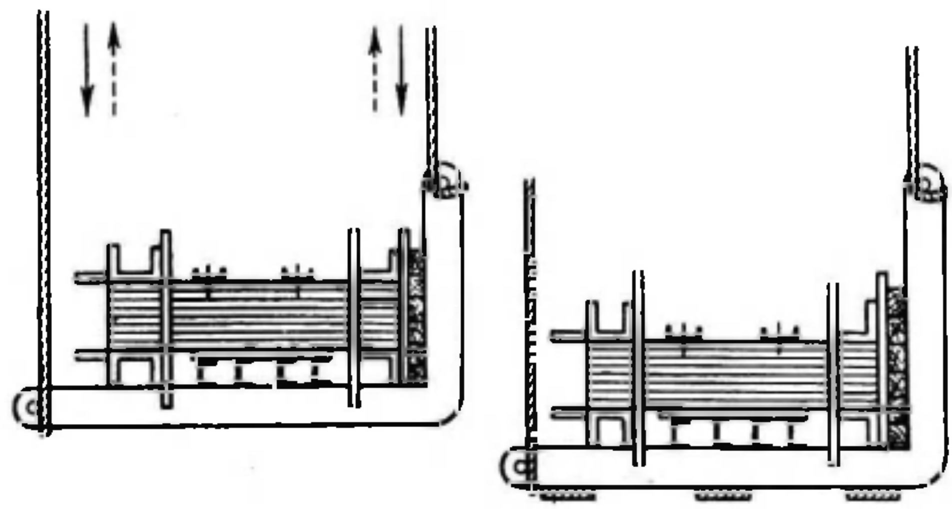
The core should be placed carefully and smoothly so as not to deform its laminations and limbs. The cores of transformers of up to 100 kV A are placed on a special table or trestles provided with transverse planks or steel channels arranged in such a way as to provide access to the clamping studs from below.

Before disassembling the core, one should draw a sketch bearing information as to the height of the core windows, the centre distance between the core limbs, the thickness of the core packets or stacks, and the location of the earthing strips, oil ducts, and insulation components.

Then the core yokes are unclamped by undoing the nuts on their clamping studs or half-ring binding clips. The nuts are first slackened uniformly and then removed. After that, the top and bottom yoke clamps and their insulation ear taken down. Then the core limbs are unclamped in both directions from the centre. The clamping studs are withdrawn from their holes, inspected, and placed on a rack. Where the limbs are clamped with steel binding bands, the latter are removed by carefully cutting them along their welds, the limbs being preliminarily compressed by means of C-clamps.

Then the core is unbladed along its entire contour, the laminations being sorted according to their width and

IV V



of a core on a tilter

III—tilting the core from vertical into horizontal position; *IV*—lowering the
4—core; *5*—wooden support blocks; *6*—clamping studs and channels

stacks they belong to and placed on portable racks. To ensure the proper stacking of the laminations when reblading the core after repair, it is necessary to draw sketches showing the arrangement of the laminations in the last two layers.

As the core is being disassembled, the laminations are inspected and faulty ones, i.e., those having fractures, spots with burnt-out or sintered coating, etc. are put aside. After the core has been completely unbladed, old insulating strips are removed from the bottom yoke clamps, the damaged laminations are repaired or replaced, and all the core laminations are prepared for re-insulation.

Cleaning the Laminations from Old Insulation

Damaged laminations are repaired if their number is not very great, otherwise they are replaced. The laminations are repaired on a special table or on a workbench. They are cleaned of the products of decomposition of oil with wire brushes and then their burnt edges are carefully cut off by means of shears. After that, the laminations are thoroughly deburred and their sharp edges are filed away. The filed laminations are dressed with a mallet. If the condition of the lamination insulation is generally good, only spots with burnt-out or otherwise damaged coating on the laminations

are re-insulated by applying a thin layer of enamel No. 1201 with a stiff brush or a sprayer. After being exposed to air for 3 hours, the laminations can be stacked.

Where all the laminations require re-insulating, old lamination insulation is removed completely. Depending on the repair conditions and the type of the old lamination insulation, laminations may be stripped of their coating in several ways, namely, mechanically, by burning, chemically, and by soaking in hot water.

The mechanical method is only used for removing insulation from laminations of hot-rolled steel. Such laminations are skinned at an angle to the steel rolling direction with wire wheel brushes on brushing machines.

The method of burning is most frequently used for removing old paper insulation. The burning of insulation is carried out either on a conveyer equipped with electric heaters or in a special oven at a temperature of 300 to 450°C. Ashes remaining on the surface of the laminations are easily carried away by ventilation means, while solid deposits are removed with brushes.

The chemical method is mainly used for removing varnish and glass insulation. By this method, laminations are immersed in a special bath filled with an 18- to 20-percent solution of caustic soda or a 25-percent solution of trisodium phosphate. It is recommended to use a 45-percent solution of caustic soda, rather than dry caustic soda, as the starting material. To accelerate the process of old insulation removal, the solution in the bath is heated to a temperature of 90 to 95°C and stirred constantly. After holding them in the solution for 15 to 20 minutes, the laminations are taken out of the bath, carefully washed with hot water, and dried then and there.

Good results are obtained when removing paper insulation from laminations by soaking it in hot water. To avoid rusting, the laminations are thoroughly dried as soon as they are removed from hot water.

Varnishing Laminations and Baking the Varnish Coating

Where the batch of laminations to be varnished is not very large, varnish coating may be applied with a brush or

a sprayer. However, a better-quality coating is obtained when varnishing laminations on a conveyer-type varnishing machine (Fig. 6.5). Laminations *1* are delivered to the table of the machine whence they are passed between rotating rubber rolls *2*. The top roll is uniformly coated over its entire length with varnish trickling from holes in a horizon-

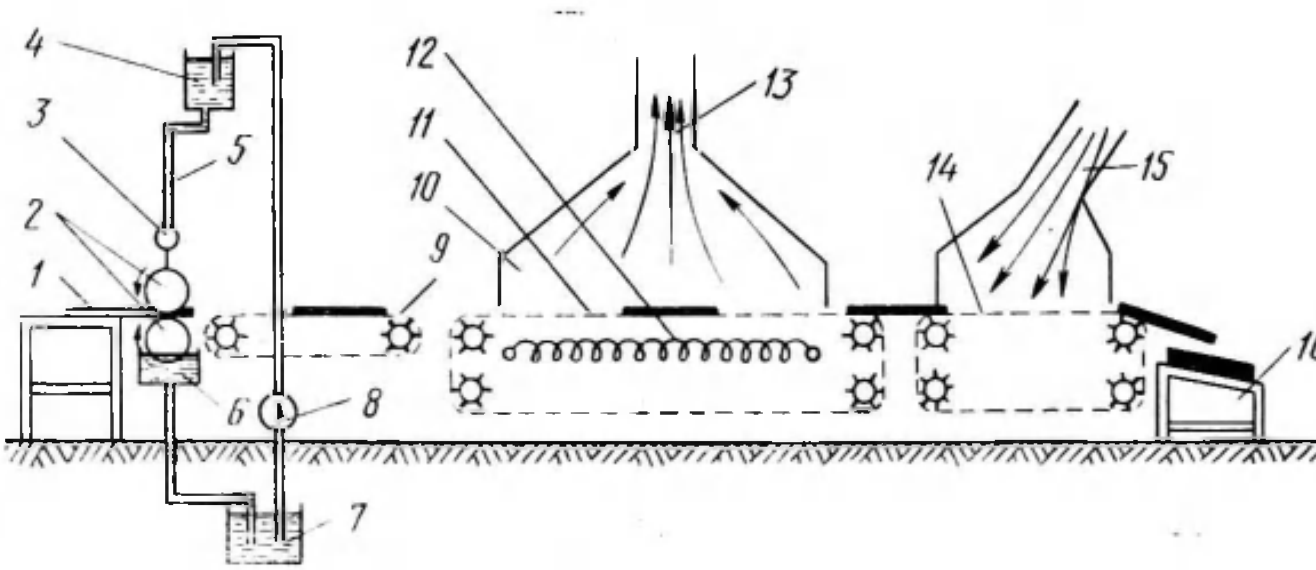


Fig. 6.5. Schematic diagram of a varnishing machine

tal header *3*. The bottom roll, while rotating, entrains varnish from a pan *6* and thus gets uniformly coated with it, the pan being filled with varnish dripping down from the top roll.

From a tank *7* varnish is pumped by a pump *8* back into the supply tank *4* whence it is fed by gravity to the top roll via a pipe *5*. While passing between the rolls, laminations become coated on both sides with a thin varnish film, and then they are transferred by a conveyer *9* into a travelling oven *10* for baking the varnish coating. The oven is a metal frame covered with heat insulation of refractory bricks or asbestos-cement plates. Under the working part of the oven conveyer *11* there are electric-heater coils *12*.

As the varnished laminations pass through the hot zone, the varnish solvent burns out and a hard varnish film forms on the laminations. The products of combustion are exhausted through a stack *13*, and the baked laminations get onto a conveyer *14* where they are cooled down to a temperature of 30 to 40°C by a jet of cold air coming from a tube *15* (water may also be used for the purpose). Then the laminations get

onto a receiving table *16* from which they are taken for a repeated varnishing or for re-assembly.

The thickness of the varnish coating is controlled by changing the force the rolls are pressed together. In single-stage varnishing, the two-side thickness of the varnish coating must be within 0.01 ± 0.004 mm, in double-stage varnishing, it must be within 0.02 ± 0.006 mm, and in triple-stage varnishing, 0.032 ± 0.008 mm. The core laminations of transformers of up to 6 300 kV A are varnished just once, while those of larger units may require a double- or even a triple-stage varnishing.

Economically, it is not worth while to make a conveyer-type varnishing machine for individually varnishing the core laminations of a transformer of a comparatively low capacity. In such cases, the laminations are varnished and baked separately. The varnishing is carried out on a power or hand-driven machine resembling the first work station of the above-described varnishing machine. For baking, the laminations are hung by hooks on a special metal support which is then placed in a drying oven provided with exhaust ventilation means.

After varnishing and baking, the laminations must have a smooth, even surface without varnish runs, and the varnish film must not separate from them. The colour of the laminations must be from brown to dark brown, and the thickness of the varnish coating must be within the specified limits. Therefore, in the process of varnishing, the thickness of the varnish coating, the insulation resistance of the laminations, and the composition of varnish are periodically checked. The D.C. resistance of the varnish coating is measured by means of a special instrument.

Re-Assembling the Core

Depending on their size, cores may be re-assembled on tilters, metal tables, or special fixtures. Such a table *10* (Fig. 6.6) is equipped with two pairs of sliding supports—two transverse beams *1* and two longitudinal beams *9*—this permitting one to set them so as to suit the size of the core to be re-assembled. The top and bottom yoke clamps *2* of the LV side are placed across the beams *1*. The distance

between the yoke clamps must correspond to that indicated in the sketch of the core.

To prevent the laminations of the core limbs from sagging, an intermediate support *5* with wooden backings *4* on top is installed between the yoke clamps.

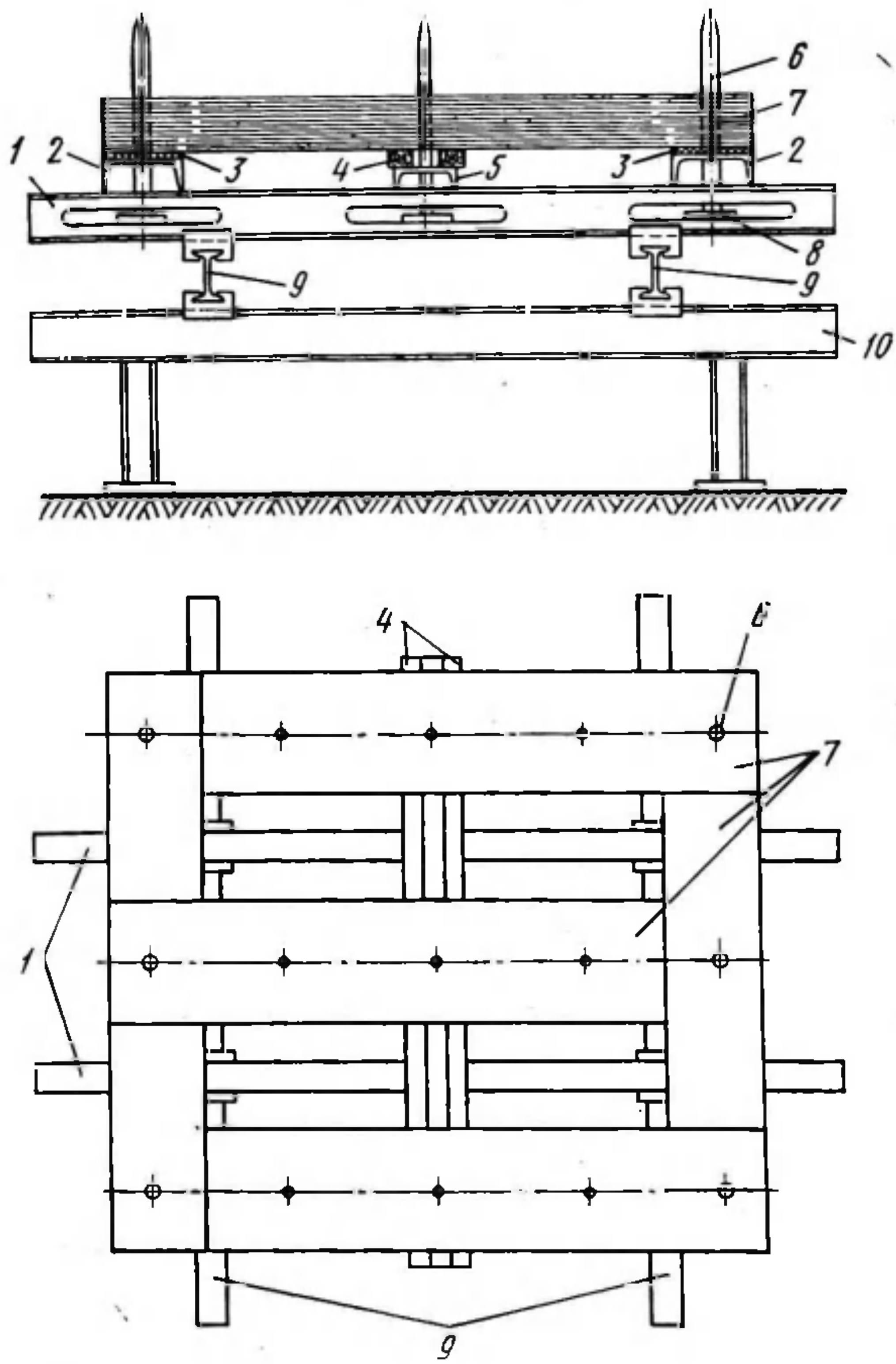


Fig. 6.6. Assembling the cores of medium-size transformers

The order of re-assembly of transformer cores is opposite to that of their disassembly. Pressboard strips *3* that insulate the yoke clamps from the core steel are placed on the

clamps and then the necessary number of aligning bars *6* are inserted into the holes in the clamps, the ends of the bars resting upon steel support strips *8*. The aligning bars should be installed along the entire perimeter of the core so as to ensure that there are not less than two bars per lamination. The diameter of the bars must be slightly less than that of the holes in the laminations. Then the stacking of laminations *7* is started.

The cores of transformers of up to 400 kV A inclusive are re-assembled by one worker, while those of more powerful transformers require two workers to re-assemble. All the

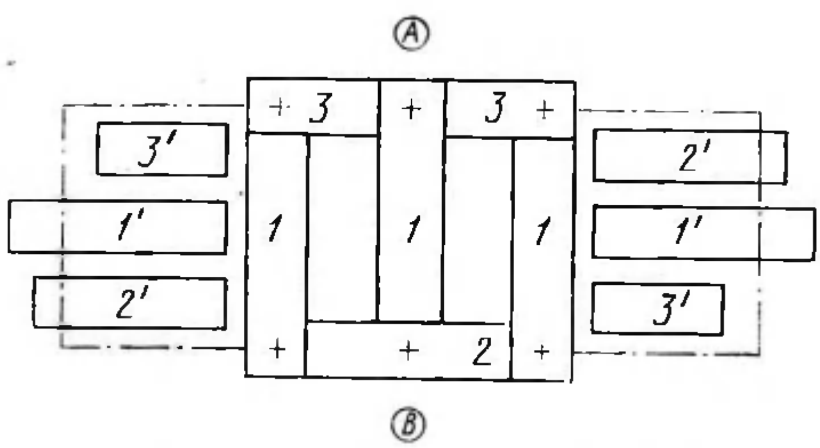


Fig. 6.7. Diagram of workplace organization when the core is assembled by one or two workers

A and *B*—workplaces; *1*, *2*, and *3*—assembled laminations; *1'*, *2'* and *3'* —laminations prepared for assembly

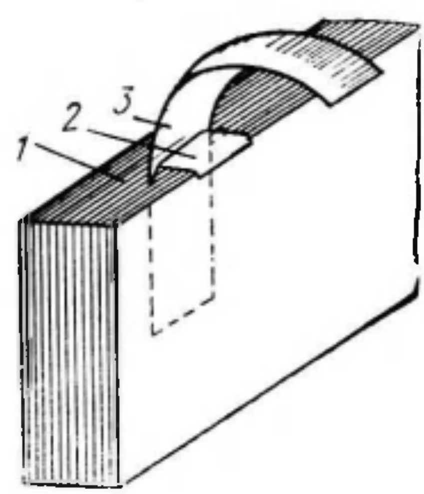


Fig. 6.8. Installation of an earthing strip

1—laminations of the second yoke packet; *2*—pressboard strip; *3*—tinned copper strip

insulating components, clamping studs complete with their insulation, washers and nuts, earthing strips, and insulated laminations must be brought to the place of re-assembly beforehand. The stacks of laminations must be located at the workplace in such a manner, as to ensure that each workman on the spot can easily get a lamination of any size without unnecessary movements.

Figure 6.7 illustrates a most advisable way of keeping the workplace when re-assembling the cores of medium-size transformers. The re-assembly starts with placing the end laminations intended to overlap the first butt joints. Then, according to the sketch drawn during disassembly, the first packet is stacked by putting laminations on the aligning bars.

The cores of medium-size transformers of Soviet make are usually stacked with two (sometimes three) laminations in a single layer. In each particular case, the number of laminations in a layer may vary and therefore, must be specified at the time the core is disassembled. The laminations must be placed regularly, without distorting the shape of the core; there must not be any protruding ends and the laminations must not get one upon another. Any irregularities and too wide gaps in the butt joints between the laminations are eliminated in the process of re-assembly with a hammer and a vulcanized-fibre pad.

To make sure that the laminations are being placed correctly, so that the shape of the core is not distorted, the distances along the diagonals between the corner holes in the core are periodically measured with a rule; these distances must be equal. The thickness of the stacks is measured with sliding callipers, and the aligning bars are checked for verticality with a triangle.

When stacking the second packet, earthing strips are inserted between the top yoke laminations. To prevent an earthing strip from short-circuiting the edges of the laminations it passes over, a pressboard strip *2* (Fig. 6.8) is placed under it.

While stacking the core, one should periodically turn the aligning bars so as to align the holes in the laminations.

The stacking is ended with placing the end (long) corner laminations that overlap the butt joints between the laminations in the next to last layer. Then the pressboard strips (either repaired or new) that insulate the core steel from the yoke clamps on the HV side are put in place and the yoke clamps are installed on top of them. After that, the aligning bars are removed in turn and clamping studs are inserted in their place.

Before being clamped with the studs, the core is somewhat swollen, because its laminations do not fit one another tightly. Therefore, the core is preliminarily compressed either by placing weights upon it or by clamping it with temporary extra-long studs. Then the thickness of the entire core is checked, paper-base laminate tubes and pressboard and steel washers are slipped on the core clamping studs, nuts are screwed on them, and the core is slightly clamped. After that, all irregularities are finally eliminated with a hammer

and a vulcanized-rubber pad and the core is clamped until its thickness reaches the size indicated in the sketch by tightening the nuts on the clamping studs, starting with the central ones, with double-ended or socket wrenches. Then the support planks are secured to the bottom yoke clamps.

The re-assembled core is slinged, lifted and put into a vertical position, sleepers or wooden blocks being placed under the support planks. Then the vertical tie-rods are installed in place, just as they were mounted before disassembly, all the nuts on the clamping studs are finally tightened up, and the insulation resistance of the yoke clamps and the core clamping studs with respect to the core steel is measured with a megohmmeter. If there are no defects, the core is sent for tests. Should the test results prove satisfactory, the top yoke is unbladed and the work on mounting the windings in place is started.

Specific Features of Repairing and Re-Assembling Transformer Cores Clamped Without the Use of Through Studs

Such cores, like those clamped by through clamping studs are positioned, disassembled, and re-assembled with the aid of a tilter. They are unclamped by removing the external clamping studs (or steel boxes) and half-ring binding clips from the yokes and the binding bands from the core limbs. The process of restoring the laminations in this case does not differ from the one described above.

The re-assembly of the core requires great care and attention, for the laminations here cannot be aligned by means of aligning bars, so the quality of stacking wholly depends on the thoroughness on the part of repairmen. The laminations in each packet 15 to 20 mm thick are aligned with a mallet, and the correctness of stacking is checked against a pattern. After all the laminations have been stacked, beechwood strips and rods are placed at the corners of the steps on the core limbs, exactly in the same order as they were installed prior to disassembly, and temporarily fixed in place with surgical tape.

Then the core is compressed by means of C-clamps and temporary binding chains or bands. First the core limbs and

then the yokes are compressed. After the thickness of the core has reached the size indicated in the drawing, the temporary clamping means are removed in turn and replaced by steel binding bands which are tightened with a force of 1500 to 1800 kgf, pressboard strips being placed under the bands. The ends of the bands are passed through plastic-coated buckles, pressboard strips are placed between the bands and the buckles, and then the ends of the bands at places where they leave the buckles are bent backwards with a hammer and electric-welded to the bands.

The yokes are compressed with temporary clamping studs inserted into special holes provided at the ends of the yoke clamps and then their half-ring binding clips and external clamping studs (or steel boxes) are installed in place and their nuts are tightened. The finally re-assembled and clamped core is checked by measuring the insulation resistance of the yoke clamps, half-ring binding clips, and binding bands relative to the core steel with a megohmmeter.

Wherever possible, the steel binding bands on the core limbs should be replaced by bindings of Grade ЛСБТ glass tape. This method of binding the core limbs is more perfect and reliable, but it requires special equipment to implement. When changing over to glass binding tape, one should calculate the required number of bindings, their thickness, and the number of layers in a single binding.

When repairing transformer cores clamped without the use of through studs, the following requirements should be met:

1. The gaps in the joints between individual laminations must not exceed 2.5 mm and the ridges formed by the laminations on the core surface must not be higher than 2 mm, the number of laminations showing such irregularities being not more than 5 in a thousand.
2. The swelling of the core at places where the laminations are butted must not exceed 1% of the thickness of the core limb or yoke.
3. The earthing strips must be cleaned bright, the core laminations at places where the earthing strips are inserted between them being not cleaned.
4. Weights must not be applied to compress the core.
5. The skew of the binding bands must not exceed 5 mm.

6. The insulation resistance of the structural components (yoke clamps, binding bands, etc.) must not be lower than 2 megohms.

7. When being tested by the applied voltage at a frequency of 50 Hz, all the clamping components must withstand for 1 minute the following voltage relative to the core steel: 2 kV for transformers of up to 6.3 MV A and 3 kV for those in excess of 6.3 MV A.

6.5. Repairing and Making the Windings

The mechanical strength of the windings decreases with time and the properties of their insulation gradually deteriorate (the insulation ages). The ageing of the interturn insulation is particularly adverse, since its wear is the most frequent cause of turn-to-turn short circuits. Therefore, windings with such insulation are either replaced or re-wound, the winding conductor being completely re-insulated and the insulating components, replaced. An accidental damage to the windings usually entails the burning-out of the conductor and insulation in the region of a turn-to-turn short circuit. Such windings are partially rewound.

The main operations in repairing the transformer windings include the re-insulating of the winding conductor, preparing of insulating components and materials, winding of coils, and drying, impregnating, and compressing of the finished windings.

Re-Insulating of the Winding Conductor

The process of re-insulating of the winding conductor consists in removing old insulation from it and then annealing, dressing, and insulating anew the bare conductor. To remove old insulation and anneal the conductor, the winding is unwound into separate coils which are then heated to a temperature of 500 to 600°C in a closed-top furnace where the insulation burns out and the internal stresses in the conductor are relieved, so that the conductor copper becomes "soft". To prevent the conductor from entangling during annealing, the coils are preliminarily bound with wire and mounted on special supports.

Also widely used in repair practice is a mechanical method of removing old insulation from winding conductors, whereby the conductor is drawn through a device where its insulation is cut lengthwise and then removed by scrapers and dressed. This device may also use drawing dies making it possible to re-draw the conductor to another size. After re-drawing, the conductor is subjected to a stress-relief annealing.

The annealed conductor, while still hot, is washed with clean water, owing to which it becomes well cleaned from

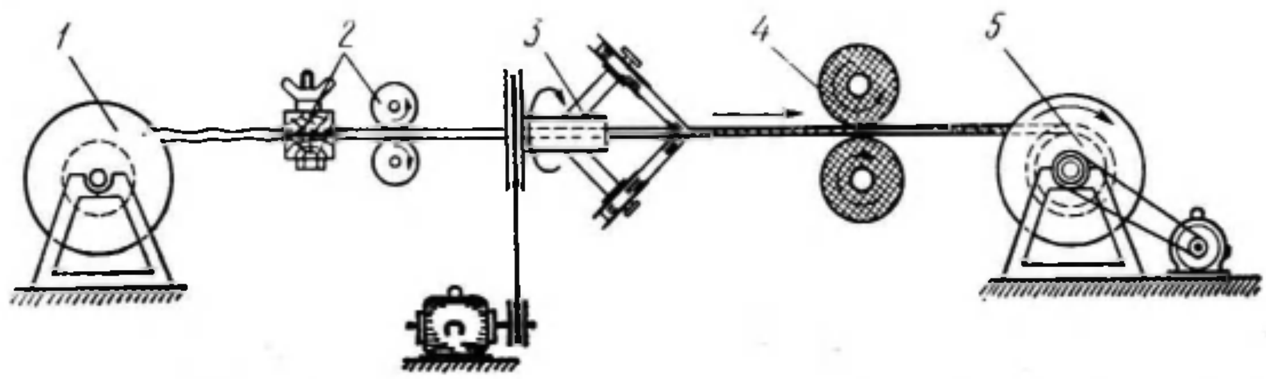


Fig. 6.9. Schematic diagram of a paper-braiding machine

burnt insulation and does not lose its softness. Then the conductor is dressed by drawing it through a system of steel rollers and carefully wound turn by turn around drums. To avoid excessive bending of the conductor, use is made of drums not less than 400 to 500 mm in diameter. Badly deformed sections of the conductor are dressed with a mallet.

The ends of the conductor in separate coils are lapped and electric-brazed with a silver spelter. The brazed connections are carefully filed and ground with emery paper. The conductor thus prepared is then insulated on special paper-braiding machines (Fig. 6.9).

The process of insulating the conductor on such a machine is as follows. The conductor is unwound from a drum *1* and is drawn by a pulling device *4* through a dressing device *2* consisting of horizontal and vertical rollers and then through a paper braider *3* which orbits round it, and then it is wound around a receiving drum *5*. While it passes through the paper braider carrying rolls of cable paper, the conductor is braided with paper tapes up to the required thickness (the turns of the paper tapes can be made to overlap one another by one-half of the tape width, by one-third of the tape width, etc.). Use is made of cable-paper tapes 10 to 25 mm wide

and 0.08 or 0.12 mm thick in various combinations, depending on the required insulation thickness and the size of the conductor.

If there are only a few metres of the conductor to be re-insulated, this is done by hand.

Preparing of Insulating Components and Materials

Before starting the work on re-winding the transformer windings, whether partially or completely, one should prepare all the required insulating components and materials. Their list and amount depend on the type of the windings and the scope of work on their re-winding. In the case of single- and double-layer windings, it is necessary to prepare paper-base laminate edge-blocks, cleats for forming oil ducts between the winding layers, pressboard wedges for making edge-blocks, strips of varnished cloth, insulating tape, etc. For multiple-layer cylindrical windings, one should prepare new paper-base laminate cylinders, should the old ones prove to be damaged, pressboard strips, edge-insulation strips, cable paper for interlayer insulation, spacer bars for forming cooling ducts between the winding coils, pressboard boxes, etc. In any case, the list of the insulating components which need be replaced is specified when inspecting the damaged windings.

No matter what type the windings are, the workplace must be supplied with linen-finished and surgical tape and 20 to 25 mm wide strips of varnished cloth, cable paper, and telephone-cable paper. There must be freshly-prepared phenolic varnish and water-soluble methyl-cellulose cement for bonding and cementing the insulating components, as well as solder for soldering the winding conductors.

In the case of partial re-winding, the new insulating components are made after the pattern of the old ones, while where the windings are re-wound completely, these are made to drawings.

Winding of Coils

The winding of coils is one of the most critical operations in repairing transformers, since it is necessary not only to keep to the required creepage distances, number of turns and

dimensions of the winding, but also to observe strictly the technique of each operation involved. When performing these jobs, one should use calculation papers and drawings of the windings. The winding coils are wound on special winding machines equipped with a horizontal spindle which carries a template. Figure 6.10 shows a machine for winding coils of Size I and II transformers.

The winding machine is driven by an electric motor and is controlled by means of a pedal *10*. For counting the number

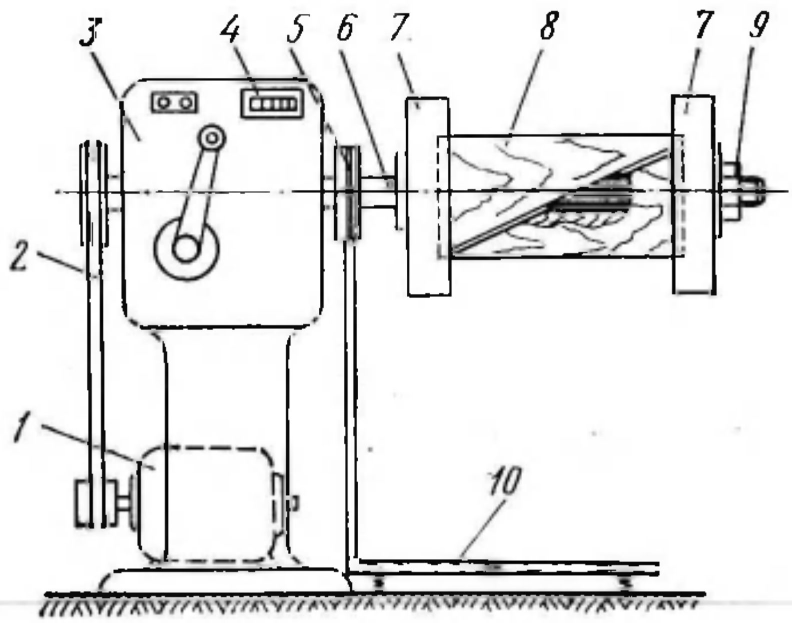


Fig. 6.10. A machine for winding coils of Size I and II transformers

1—electric motor; *2*—driving belt; *3*—bed; *4*—revolution counter; *5*—clutch; *6*—spindle; *7*—paper-base laminate plates; *8*—template; *9*—template fastening nut; *10*—control pedal

of turns, the machine is provided with a revolution counter *4*. When winding helical and continuous-disk coils, use is made of a split or solid metal template, while a split wooden template *8* with a diagonal cut is employed for making small layer-by-layer windings. The template is mounted on the spindle of the machine and is clamped by two paper-base laminate plates *7*. Such a template design facilitates the removal of the finished coil: for this purpose one has only to take down the paper-base laminate plate from the end of the spindle and move apart the wedge-like halves of the template.

Along with the winding machine, a number of small devices and tools are used when making windings. These include special appliances for clamping and bending the winding conductor, electric-brazing tongs for hard-soldering copper conductors, appliances for welding aluminium

conductors, wire and ordinary shears, files, hammers, knives, etc.

If the drum holding the conductor is located behind the winder facing the machine, a right-hand coil is wound starting from left to right, while a left-hand one, in the opposite way—from right to left. If the conductor drum is located in front of the winder (behind the machine), the winding direction is reversed.

Before starting the work on winding the coils, one should check the size of the conductor with a micrometer.

The finished coils are removed from the machine and placed on special felt-covered supports.

The winding of coils is a very laborious operation requiring practice and high skill. Under plant conditions, the coils are wound by specially trained persons—winders—while when repairing transformers directly at the place of their installation, this operation is carried out by highly skilled workers performing both as electrician-mechanics and winders.

Drying, Impregnating, and Compressing of Windings

After helical or continuous-disk windings have been wound, coil-end insulation rings are mounted on them and the ends of their conductors are bent as required and insulated. Such windings, immediately after winding, have an increased axial size as compared with the design one, therefore, they are clamped each between two metal plates held together by steel studs, wooden backings being placed between the coils-end insulation rings and the plates in line with the columns of the interturn or interdisk spacers, and then dried. The top plate is equipped with springs (usually of the disk type) under the action of which the windings are automatically compressed as their insulation dries out and shrinks.

Under plant conditions, the windings are dried in a vacuum in a special oven, while under individual repair conditions, they are dried without vacuum in an oven equipped with an electric heater or in a closed metal tank provided with a winding for induction heating. After being dried for 10 to 15 hours at a temperature of 100 to 105°C, the windings are additionally compressed by uniformly tighten-

ing up the nuts on the clamping studs until the design axial size of the windings is reached. After drying and final pressing, the windings of Size I transformers, some windings of Size II transformers, and all layer-by-layer windings are dip-impregnated with Grade MЛ-92 varnish and baked in order to make them solid and sufficiently strong mechanically. To improve the quality of impregnation, the windings are heated to a temperature of 50 to 70°C prior to dipping. The impregnation time ranges from 15 to 40 minutes, depending on the size, construction, and voltage class of the windings. The impregnated windings, after surplus varnish has trickled down, are placed in an oven where they are baked for 10 to 12 hours at a temperature of 100 to 105°C.

To give the windings mechanical strength, when they are being made without impregnation and baking, the winding turns are placed more tightly, the conductor tensioning being increased, the windings are reinforced with external cleats, and dried in a compressed state. The helical and continuous-disk windings of transformers of Size III and over are wound on machines equipped with a tailstock, such as Models T-21 and T-23, where the template is mounted between the live and dead centres. In any case, helical and continuous-disk coils are dried after winding.

After winding and drying, the coils are compressed between special plates in a press and then finished, i.e., the projecting ends of the spacer bars and wedges are cut off, loose ends of insulating tapes are trimmed, the bulging transpositions of the conductors are tapped down, the ends of the conductors are cut and placed according to the drawings of the windings, and the columns of the interlayer interdisk spacers are lined up (for this purpose the windings are temporarily released). After finishing and final pressing, the windings are clamped with steel frames in which they are shipped and stored until it is time to mount them on the core.

6.6. Repairing and Making the Major Insulation

When transformer repair includes the replacement of the windings, the major insulation, as a rule, is also replaced by new one. Where the windings are restored, old insula-

tion is sometimes used again. If it is only slightly damaged, the major insulation is repaired by replacing its individual components by newly made ones. In Size I through III transformers, the yoke and coil-end insulation are, as a rule, made anew.

Pressboard insulation is made using the following tools and devices: a machine tool or device for cutting out annular disks (e.g., circular shears), vibration, parallel, and hand

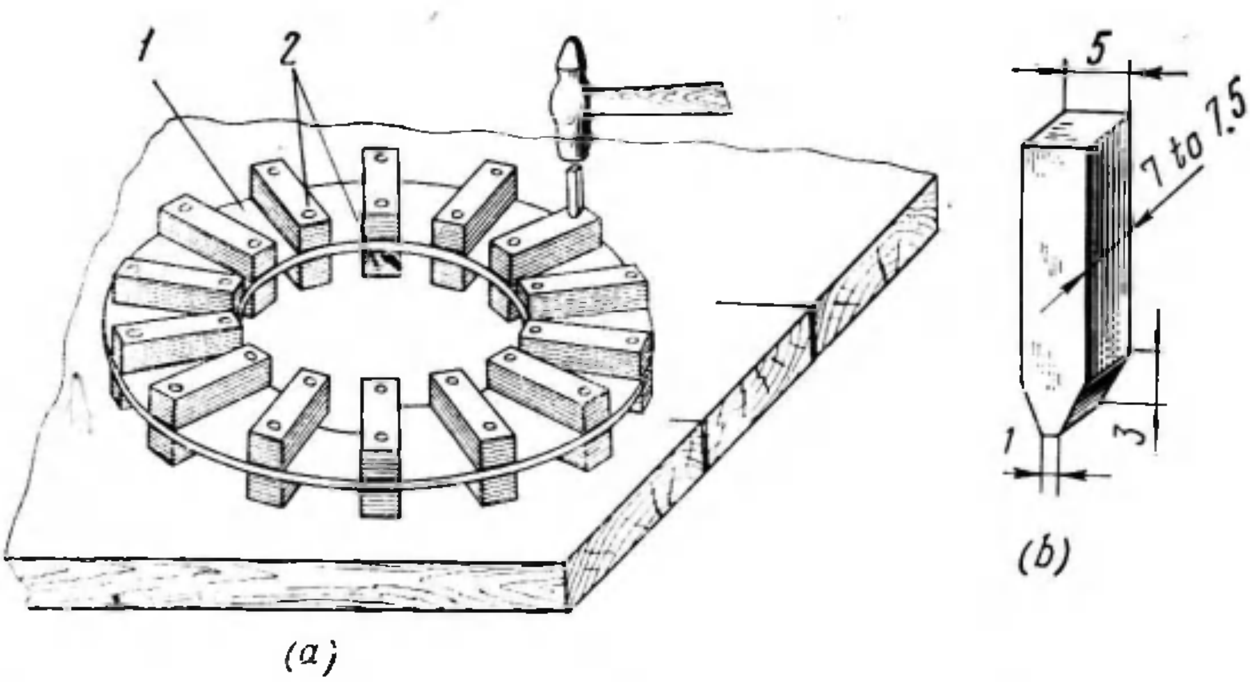


Fig. 6.11. Assembling the yoke insulation of a Size III transformer
(a) yoke insulation; (b) pressboard rivet

shears, an electric or hand drill with a bit 7.2 mm in diameter, a bench hammer, a brush for applying a coat of varnish onto components to be cemented together, a table for marking out, varnishing, and assembling the insulation components, and a device — a press mould — for pressing and baking the cemented components.

Figure 6.11*a* illustrates the assembly of the yoke insulation of a Size III transformer. The annular disk *1* is cut out from a sheet of pressboard 2 to 3 mm in thickness. The top and bottom spacing blocks are stacked up of separate pressboard strips. These strips are cut out from a sheet of pressboard in a definite direction — either with or across grain — since pressboard shrinks differently with and across grain. Should arbitrarily cut pressboard strips be cemented toge-

ther, this will result in their warpage and cleavage after drying.

The strips are given a coat of phenolic varnish (with a brush or by means of special rolls), dried in air for 7 to 8 hours, and then stacked up to the required thickness and banded with a tape of cable or crepe paper applied in a staggered fashion. The spacing blocks thus obtained are then pressed and baked in hot press moulds compressed by disk springs. After 8 to 10 hours' baking, the spacing blocks are released from banding and cleaned from varnish that has oozed out, and then their lateral surfaces are smoothed on a special milling device.

Where methyl-cellulose cement is used, the drying time is cut down to 30 minutes.

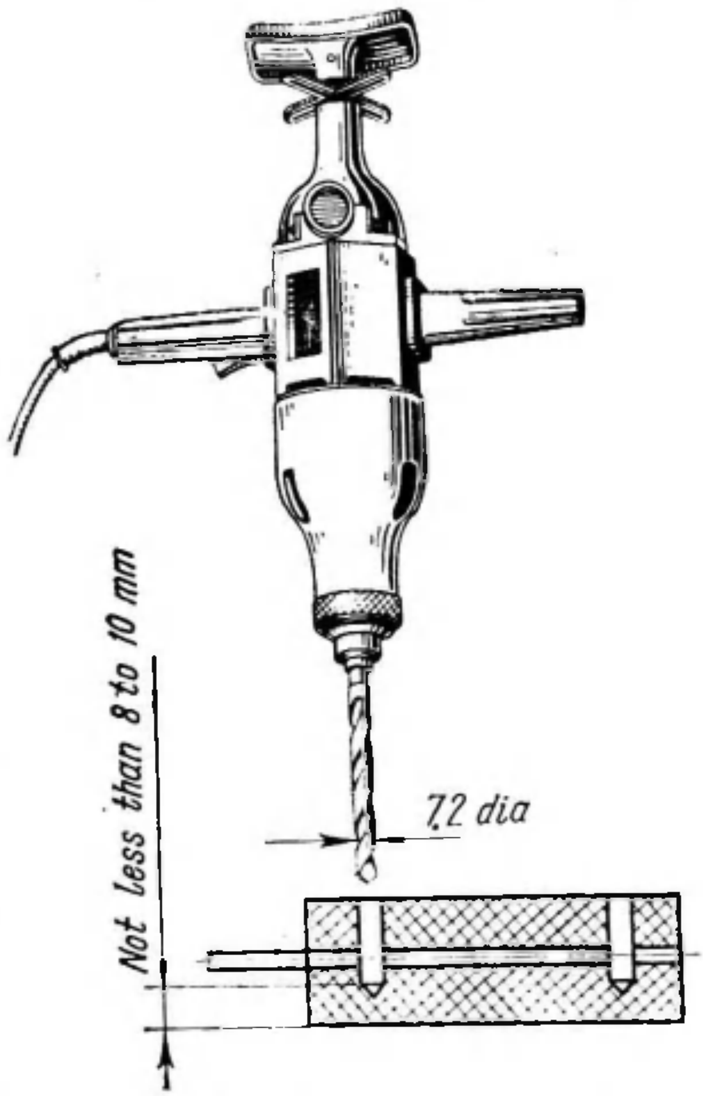


Fig. 6.12. Drilling holes to fit rivets

Then the places where the spacing blocks are to be installed are marked with chalk on the annular disk, the blocks are put in place, and holes to fit rivets are drilled in the blocks and the disk at one go. One of the two spacing blocks in a set is drilled through, while the other, only to a depth of not more than 0.25 of its thickness (Fig. 6.12).

After that, the disk complete with the spacing blocks is put on a table, the through-drilled blocks being at the top, the surfaces of the blocks in contact with the disk are coated with phenolic varnish, the blocks are installed in place, and rivets, also preliminarily coated with varnish, are driven in the holes. The rivets (see Fig. 6.11*b*) are made of pressboard. The length of the rivet must be such as to ensure that after the rivet has been driven home, its end

will be somewhat flattened, as if forming a countersunk head. With the holes 7.2 mm in diameter, the width of the rivet is taken at 7 to 7.5 mm. Each spacing block is fastened with 1 to 3 rivets, depending on its length.

The pressboard coil-end insulation is repaired and made anew in a similar way.

When repairing the major insulation, quite frequently only the annular disks are replaced, while the spacing blocks (if they are not damaged and have not lost their mechanical strength) are used for further operation after being cleaned and washed.

6.7. Fitting the Insulation. Mounting and Packing Out the Windings

Before fitting the insulation and mounting the windings in place, the top yoke of the core must be unbladed and the ends of the core limbs must be tied. The main technical papers which are followed when mounting the windings are the sketches drawn during disassembly, calculation papers, and winding drawings.

The LV and HV windings complete with their insulation are brought to the workplace. If the windings are new, one should check their voltage rating and the capacity and type of the transformer they are intended for by reading the tags affixed to them. If these data correspond to the characteristics of the transformer under repair, the windings are visually inspected for external defects and then tested for breaks and for short circuits between turns and between parallel conductors. These tests are carried out by the personnel of a laboratory.

Then the bottom coil-end insulation is placed on the flanges of the bottom yoke clamps. In transformers of up to 1 600 kV A for voltages up to 10 kV, this is a deck *1* of beechwood planks (Fig. 6.13). The planks are laid on the yoke clamps along the perimeter of the core, as shown in the figure, and checked to see whether their surface is flush with the yoke surface. Then the elements *2* of the bottom yoke insulation are fitted on each core limb *3* and made to lie on the beechwood deck and the yoke surface so that their spacing blocks do not sag.

If the windings have no rigid cylinders, use is made of soft pressboard cylinders *4* fitted on the core limbs in place of the rigid ones. The soft cylinders are made each of two rectangular sheets of pressboard 1 to 1.5 mm thick, which are bent in the form of a half-cylinder and fitted around the core limb in such a manner, as to ensure that they

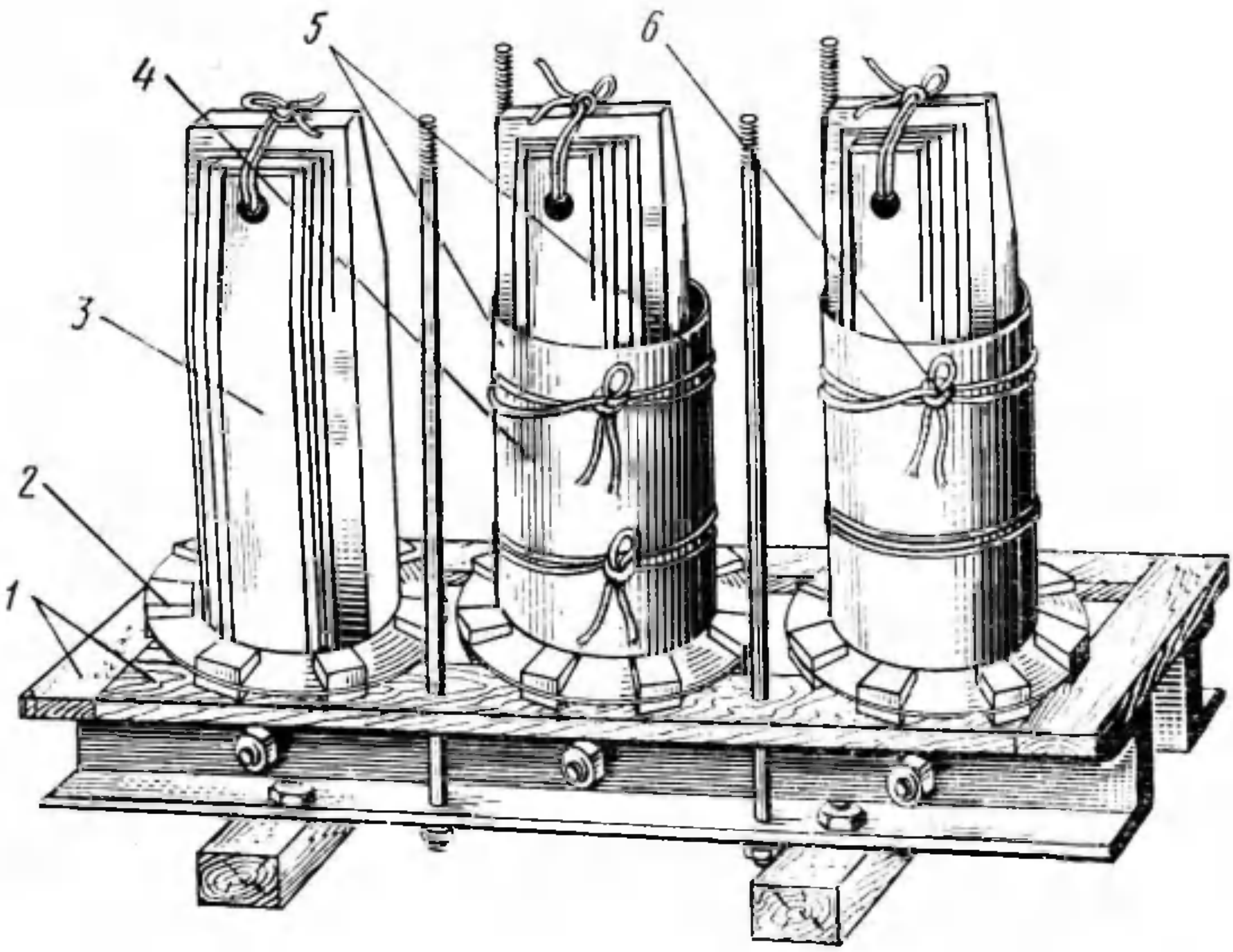


Fig. 6.13. Mounting the coil-end and yoke insulation on transformers of up to 1 600 kV A at 10 kV

form an even cylinder and overlap each other at the joints. The lap joints *5* of the half-cylinders must be located on the side surfaces of the limb and in line with its central packet. The pressboard sheets should be smoothly bent with grain, so that true cylinders, free from corners and fractures, can be obtained.

The cylinders are fixed on the core limbs with cotton tape, or they are temporarily tied round with cord *6* which is removed when mounting the windings. The height, thickness, and outside diameter of the cylinders are checked with a rule, sliding callipers, and outside callipers, respectively.

All the dimensions of the cylinders must correspond to those indicated in the drawings or sketches of the old cylinders.

Unified-series transformers of up to 250 kV A use coil-end and yoke insulation of somewhat other construction (Fig. 6.14). Here, four beechwood blocks *3* are placed at each core limb (two blocks on each side of the limb) as shown

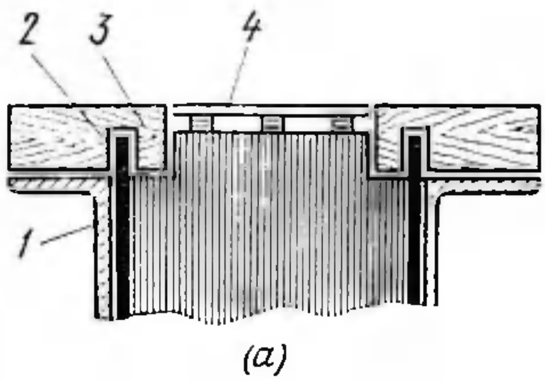
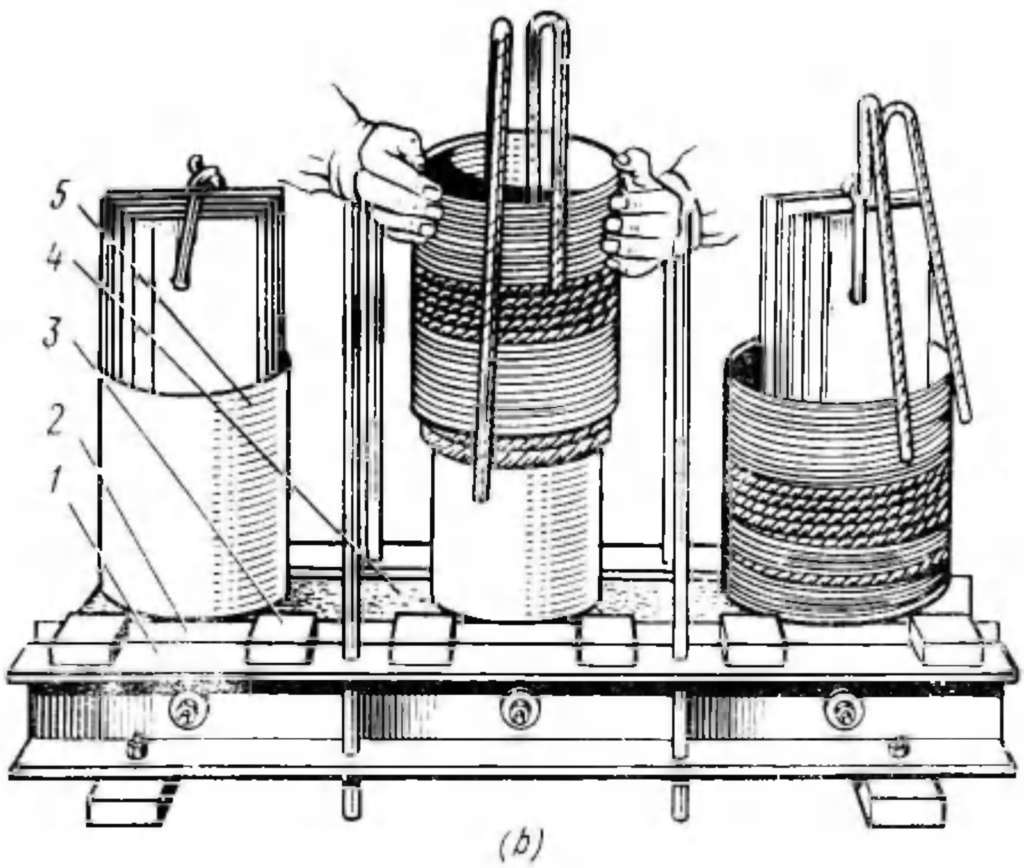


Fig. 6.14. (*a*) Design of the yoke and coil-end insulation and (*b*) mounting the windings



in Fig. 6.14*b*. The blocks have a transverse recess to fit the projecting edge of a pressboard strip *2* insulating the core steel from the yoke clamp *1*. The top surface of the blocks lies above the surface of the yoke, so they double as the coil-end and the yoke insulation. To insulate the windings from the yoke in spaces between the core limbs, the yoke there is covered with two pressboard shields *4* flush

with the blocks. Apart from insulating the windings from the yoke, these shields provide seating surfaces for the windings.

After fitting the coil-end and yoke insulation, the LV windings are mounted on the core limbs insulated by the cylinders *5*. The windings are mounted in turn, beginning with an end phase. The windings of transformers of up to 630 kV A are mounted by hand.

When mounting the LV windings, one should see to it that their line ends face the side where the LV leads will be arranged. The windings must tightly fit the insulating cylinders on the limbs, so that some effort must have to be exerted to mount them in place. If a winding offers too great a resistance when being mounted, it is necessary to check its dimensions and to reveal and eliminate the cause of trouble.

Once the LV windings are fitted in place, the HV windings are mounted concentrically on them, the line ends and voltage-control taps of the HV windings facing the side where the HV leads will be arranged.

After they have been mounted on the core limbs, the windings are packed out radially by driving beechwood battens, enclosed in pressboard boxes, in the space between the HV and LV windings, and round bars and suitably shaped strips of beechwood between the LV windings and the core limbs. This gives the windings the necessary radial rigidity and excludes the possibility of their being displaced and damaged under the action of dynamic forces.

The packing-out operation starts with driving beechwood battens between the LV and HV windings, opposite each column of interturn or interdisk spacers forming oil ducts in the HV windings. First the pressboard boxes that enclose the battens are inserted to their full length and then the battens rubbed with paraffin wax are inserted vertically between their respective boxes to a depth of 40 to 50 mm. After that, the battens are driven in with a hammer. Every other batten should be driven across the diameter from, rather than next to, the previous batten. If a batten slips in easily, a pressboard liner should be placed under it. Tightly fitting battens should be reduced in thickness by planing as much as may be necessary.

Next come the LV windings. These windings are packed out by driving round beechwood bars between the limb steps and the pressboard cylinders of the coils, and shaped beechwood strips between the flat portions of the limbs and the cylinders. The dimensions of the packing-out components and the places of their installation must correspond to those indicated in the drawing or sketch drawn when disassembling the windings. The packing-out should be done carefully, so as not to damage the windings, limb laminations, and the packing-out components themselves. It should be borne in mind that the mechanical stability of the windings under short-circuit conditions depends primarily on the quality of packing-out.

After the windings have been packed out, the top yoke insulation components are fitted on the core limbs and the ends of the LV windings are bent as required and insulated. The winding ends are bent with the aid of an elliptical tube which is used as a lever. Insulation is applied half-lap over a length of 100 to 120 mm, beginning with places where the ends of the winding conductors leave the coils. The ends of single-, double-, and multiple-layer cylindrical windings are usually insulated by applying two layers of varnished cloth, while those of continuous-disk and helical windings for voltages up to 10 kV are insulated up to a thickness of 1.5 mm on one side. A single layer of linen-finished tape is applied half-lap over the main insulation. Special care should be taken when insulating the winding ends at places where they leave the coils, since at these spots the conductors are bent and their insulation gets damaged quite frequently. The ends of the insulating tapes should be thoroughly terminated and coated with phenolic varnish.

6.8. Specific Features of Mounting the Windings of Transformers for 110 to 220 kV

The cores of these transformers are clamped with through studs, therefore, prior to mounting the insulating cylinders and windings, suitably shaped beechwood planks provided with holes to fit the ends of the clamping studs and with ducts for oil circulation are fitted on both sides of each core

limb so as to cover the projecting ends of the studs. The planks are fastened with surgical tape wrapped around the core limbs. When fitting the planks, one should measure with outside callipers the outer diameter of the core limbs across the planks and check it against the size given in the drawing of the core.

After that, the work on mounting the LV windings on the core limbs is started. High-capacity transformers use soft, rather than rigid, insulating cylinders. Such cylinders are assembled directly on the core limbs from separate blanks of pressboard 1.5 to 2 mm thick, which are stacked up to the required thickness (usually 4 to 6 mm) and made to overlap one another by 40 to 80 mm, depending on the transformer size.

The cylinders, thus assembled according to drawings, are fastened by tying them round with surgical tape applied in a staggered fashion over their entire height. To make the blanks forming the cylinders tightly fit one another, the cylinders are tied up with a cord, while being tapped round with a mallet. Large-sized cylinders are tied up by means of a special, portable hand-driven winch. After tying and fastening the cylinders, their outer diameter is measured with outside callipers, or with special sliding callipers, and checked against the size indicated in the drawing of the windings.

The windings are mounted on the core limbs with the aid of the same lifting fixture—a three-bar spread frame with draw bars and grips—as is used in dismantling them. Prior to mounting, the windings are checked for defects and for the correspondence of their dimensions to the design data.

The inner and outer diameters of the windings are measured, as well as their axial size. The sizes of the conductors are measured with a micrometer. The windings are checked for broken conductors and for short circuits between parallel conductors. In the case of helical and continuous-disk LV windings, these tests are carried out using a megohmmeter operating at a voltage of 1 000 V or a trouble lamp.

When checking the windings for short circuits between parallel conductors, the ends of the conductors are moved

apart and stripped of paper insulation with a knife. One probe of the megohmmeter is connected to one of the parallel conductors, while its other probe is connected in turn to all the other parallel conductors. When turning the crank of the megohmmeter, the instrument must not read zero. If the windings are checked with the lamp, it must not glow. Then the "fixed" probe of the megohmmeter is connected to the next parallel conductor of the winding and the other probe is connected in turn to the rest of the parallel conductors (except for the one that has already been checked). In this way, all the parallel conductors of the winding are checked.

When checking for broken conductors, all the parallel conductors at one end of the winding are connected together, while at its other end the conductors are checked in pairs with the megohmmeter. If there are no breakages, the instrument will always read zero.

Should there be short-circuited or broken parallel conductors, the seat of the trouble must be located and the defect eliminated before mounting the winding.

Helical and continuous-disk windings come in for assembly clamped down to the axial size specified in the drawing, so they must be checked for short circuits prior to unclamping, because, when unclamped, the parallel conductors may change their relative position and the short circuit, if there is any, may be cleared only to re-appear on reclamping.

After testing, the windings are unclamped, visually inspected on the outside and inside, and blown through with compressed air. Then the projecting ends of their pressboard bars and strips are cut off with a chisel and a hammer according to the drawing, i.e., at mid-height of the support ring at the top of the winding and 5 to 6 mm above the bottom surface of the support ring at the bottom of the winding.

Once the preparatory work is ended, the grips on the draw bars of the three-bar spread frame are brought under the winding, the winding together with the draw bars is tied round with a rope, and then it is lifted and moved to the corresponding core limb. The winding is aligned with the centre of the core limb and turned in such a manner,

as to ensure that its start and finish are located in the appropriate spaces between the spacing blocks of the yoke insulation.

To improve the sliding of the windings during mounting, the insulating cylinders on the core legs are rubbed with paraffin wax.

Then the winding is smoothly lowered on the core leg, while being guided by hand so as to ensure that the columns of the interturn or interdisk spacers are in line with the spacing blocks of the yoke insulation. The winding must fit its cylinder tightly, so that one or even two workers must have to exert some effort to mount it in place. If the winding offers too great a resistance, it should be lifted and the reason for this should be found. One should check the inner size of the winding across its bars and the outer diameter of the cylinder, and see that no insulating parts or conductor ends extend inside the winding. If the winding goes too easily, it should be lifted and the diameter of the cylinder should be enlarged by adding pressboard sheets.

The inner windings, usually the LV ones, are not lowered home at once. When the winding comes to a distance of 100 to 150 mm from the bottom yoke insulation, temporary wooden blocks are placed under it, the lifting fixture is removed, and the bottom end of the conductor is bent and insulated. If there are several parallel conductors, their ends are aligned and laid according to the drawing of the winding.

In transformers ranging from 1 000 to 6 300 kV A at 35 kV, the winding ends are insulated with tapes of varnished cloth or crepe paper applied half-lap up to a thickness of 4 to 6 mm on one side. The layers of insulation must tightly fit one another and must taper all the way to the end, the length of the taper being taken at 10 times the insulation thickness.

The top conductor ends of the LV windings are bent, laid, and insulated after mounting the HV windings.

Once the bottom conductor end of the LV winding is insulated, the temporary wooden blocks are removed from under the winding and the latter is tightly set on the yoke insulation so that the bottom conductor end lies in the space between the appropriate spacing blocks of the yoke insulation,

If the winding does not get home under its own weight, it is then set down with a dead-weight.

After the LV windings have been placed on the core limbs, they are packed out with round bars and shaped strips of beechwood driven between the limb steps and the insulating cylinders of the windings.

Soft insulating cylinders for the HV windings are assembled on the LV windings in the same way as the LV winding cylinders are assembled on the core limbs.

Then the HV windings are put on the core limbs, after they have been inspected and prepared as the LV windings. The HV windings are lowered onto the limbs with the aid of the same lifting fixture, with its grips applied to the windings in exactly the same manner. Again, one should make sure that the columns of the interturn or interdisk spacers are in line with the spacing blocks of the yoke insulation. The line ends and voltage-control taps should be arranged as shown in the drawing.

Because of the springiness and some swelling of their insulation, the axial size of the unclamped windings is somewhat increased and, as a result, the top yoke laminations on re-blading the top yoke abut against the insulation and do not adjoin the core laminations. Therefore, after mounting, the LV and HV windings of each phase should be separately driven down with a special device or a dead-weight which is lowered by a hoisting mechanism on special support blocks set up on the windings. The windings being compressed to their normal axial size, the top conductor ends of the LV windings are bent and insulated.

Then the set of the top insulation components is fitted, pressboard rings and then steel pressure rings being placed on the yoke insulation of the windings. The pressure rings must be a few millimetres below the butt joint between the limb and yoke laminations in the middle packet. This is required for normal stacking and butting of the laminations on re-blading the top yoke. After the core-coil assembly has been dried out and the windings have been finally clamped, this gap usually equals 10 to 20 mm. After that, the top yoke is re-bladed.

6.9. Re-blading the Top Yoke. Clamping the Windings and the Top Yoke

Re-Blading the Top Yoke

The top yoke laminations, yoke clamps, clamping studs, yoke clamp insulation, and earhting strip should be brought to the place of assembly at the start of the work. The re-blading begins with installing the middle (longer) laminations of the central stack *1* (Fig. 6.15). The yoke laminations *2*

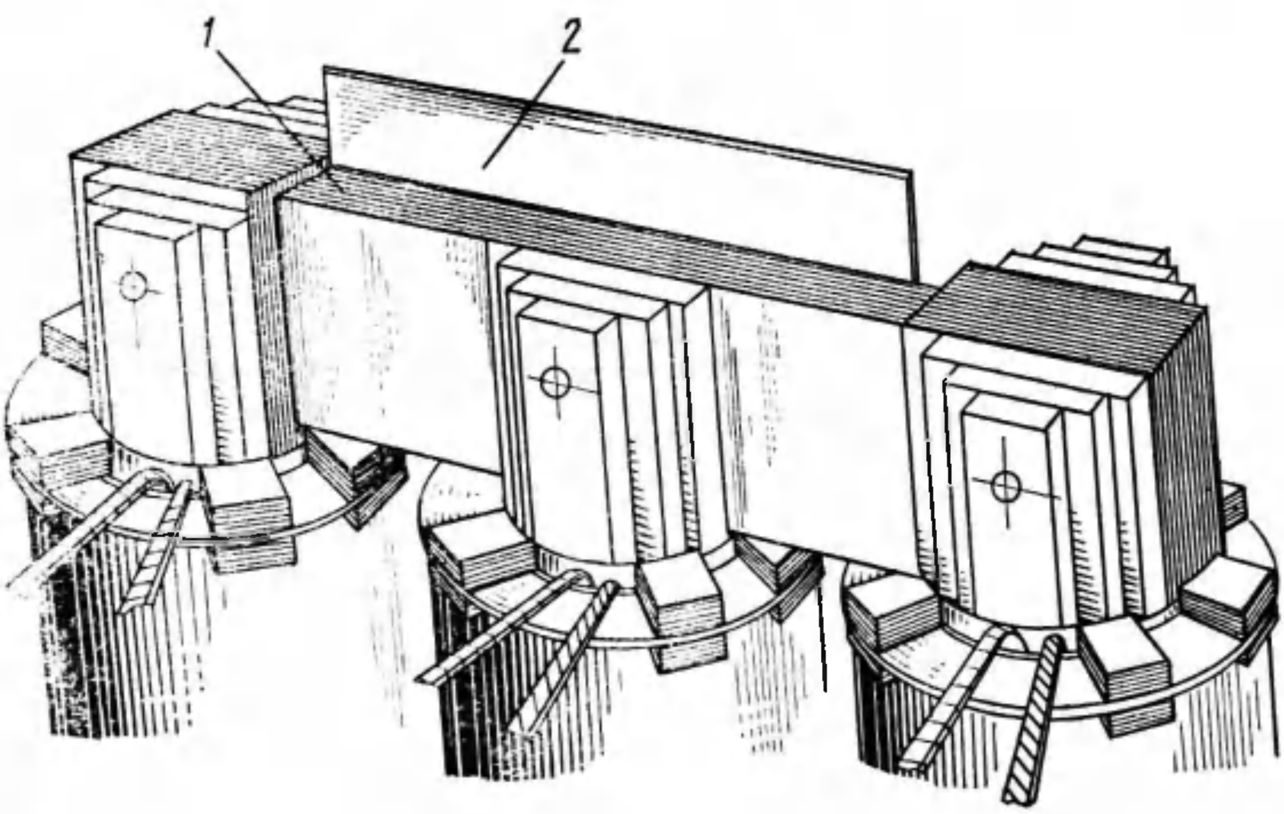


Fig. 6.15. Re-blading the top yoke

are placed between the projecting vertical limb laminations concurrently from both sides of the yoke, two or three laminations being inserted at a time, depending on the manner the top yoke was assembled formerly.

The yoke laminations should be inserted in such a way, as to ensure that they neither overlap the shorter limb laminations nor form gaps in the butt joints and that the holes in them exactly coincide with the holes in the limb laminations, otherwise the clamping studs will not go into the holes of tne re-bladed yoke.

After the middle laminations of the central stack have been inserted, the left- and right-hand corner plates of

the central stack are installed. The same procedure is followed in stacking up the other packets of the yoke, i.e., the middle laminations are installed first, then the corner laminations. It is essential that every corner plate should make an even butt joint with the respective vertical plate of the limb.

To reduce the gaps in the butt joints between the laminations and to level laminations that form ridges on the yoke surface, each layer of laminations is hammered down, the hammer being tapped against a pad of insulating material placed along the laminations. One should never strike blows directly against the laminations or use a steel pad. The plates projecting at the yoke ends are hammered in so as to reduce the gaps between the corner and successive plates of the yoke.

When re-blading the top yokes of large transformers (of 6 300 kV A and over), the yoke stacks are temporarily clamped with U-cramps to avoid excessive bulging of the laminations. The ends of the cramps are sharpened, and they are arranged in a staggered pattern over the entire width and length of the yoke. The re-blading of the yokes using laminations of cold-rolled steel, especially those with miter joints, requires special care and attention.

Clamping the Windings and the Top Yoke

Despite hammering-down during re-blading, the top yoke laminations *3* (Fig. 6.16) sometimes cannot reach the limb laminations, because they abut upon the yoke insulation. To finally set all the yoke laminations in place, the windings *9* are preliminarily compressed by the yoke clamps and vertical tie-rods *5*, the yoke being slightly clamped with temporary studs *2* inserted into the two extreme, supplementary holes in the yoke clamps.

The yoke laminations are driven down with a small sledge through a vulcanized-fibre pad 30 to 40 mm in thickness. The gaps in separate butt joints between the yoke and limb laminations must not exceed 1 to 2 mm. It should be borne in mind that greater gaps in the joints between the laminations, or lack of some laminations, cause an increase in the no-load current and core losses. This is revealed during

tests and may lead to the repeated unblading and re-blading of the yoke.

After the yoke laminations have been finally set in place, the nuts on the studs *2* are slackened and the insulating strips *4* of the yoke clamps are installed. In small cores, these are simply pressboard strips with holes for the clamping studs. In larger cores, the strips are provided with

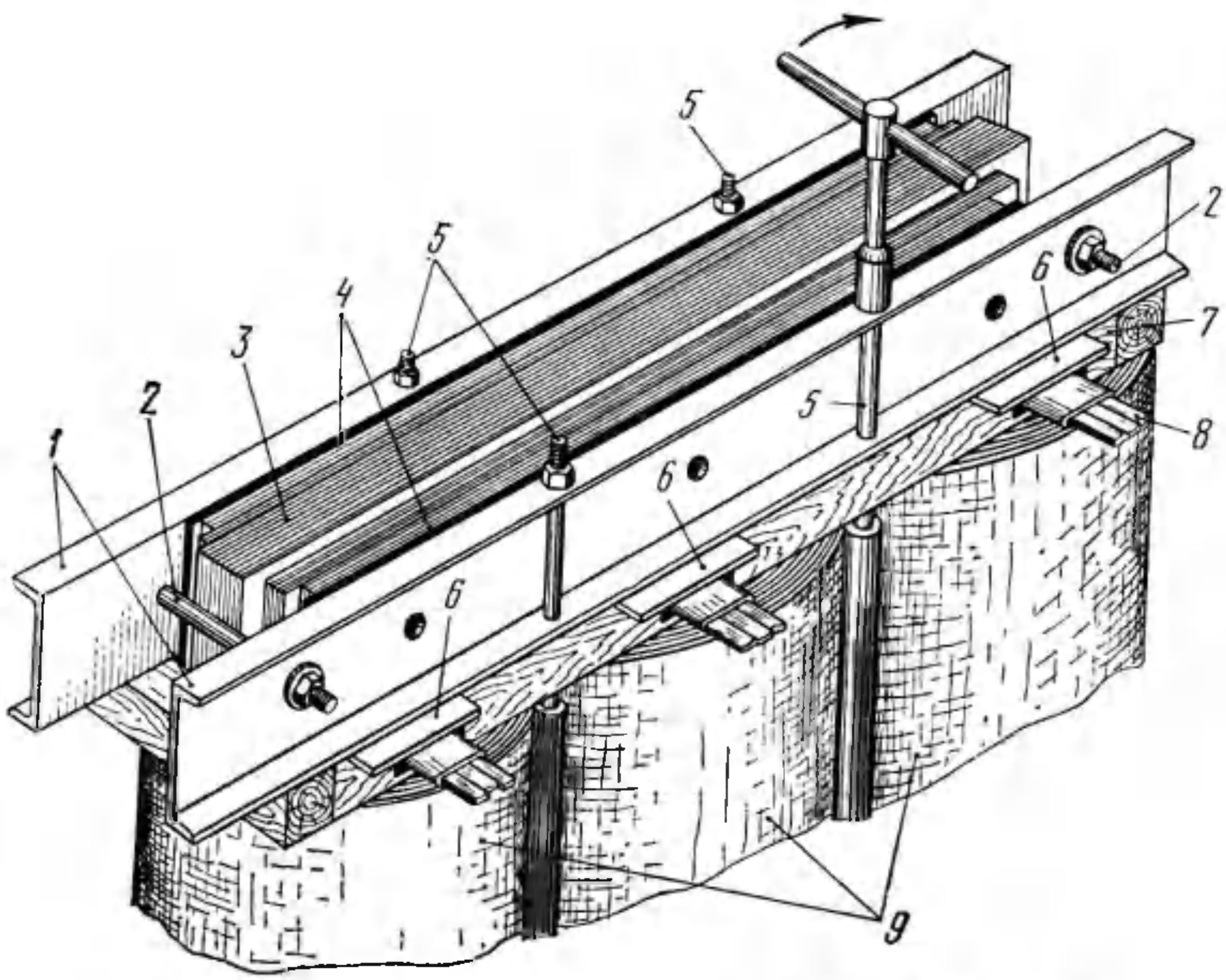


Fig. 6.16. Clamping the windings and the top yoke

transverse spacers, also of pressboard, which form vertical cooling ducts between the yoke and the yoke clamps.

To facilitate assembly, it is frequent practice to tie temporarily the strips *4* to the yoke clamps with surgical tape and mount them on the yoke together with the clamps. The yoke clamps and insulating strips are installed in such a manner, as to ensure that the holes in them are in line with the holes in the yoke laminations.

Then pressboard shields *6* are inserted between the bottom flanges of the yoke clamps and beechwood planks *7* at

spots where the ends *8* of the LV windings are brought out. These shields serve as additional insulation between the winding ends and the yoke clamps.

After that, the yoke is clamped by uniformly tightening up the nuts on the temporary studs. The holes in the yoke are inspected and if there are displaced laminations, they are aligned with a steel tapered drift. Then the yoke clamping studs together with their paper-base laminate tubes are inserted into the holes of the yoke, insulating and steel washers are slipped onto the studs from both ends, and then nuts are run onto them.

The earthing strip is installed on the LV side. One end of the strip is inserted to a depth of 50 to 60 mm between the laminations of the first yoke stack, while its other end is clamped between the web of the yoke clamp and its insulating strip.

Then the top yoke is finally clamped up by tightening the nuts on the clamping studs (the temporary studs are removed), the nuts are centre-punched, and the insulation resistance of the clamping studs is checked with a megohmmeter.

6.10. Soldering, Welding, Insulating, and Fastening the Leads

Soldering and Welding the Leads

The windings assembled on the transformer core are connected to one another and to the tap changer and terminal bushings by means of leads. The HV and LV windings of transformers of up to 100 kV A are, as a rule, connected star, with the neutral point on the LV side being made available for connection (Y/Y_n-0 connection). Larger transformers use the Y/D-11 connection. In each particular case one should refer to the winding connection diagram and to the drawings of the leads.

In transformers, copper current-carrying components are connected mainly by soldering. Also widely used is the method of electric (resistance) brazing with spelters (Grade МФ-3 phosphorous-copper spelter and Grade ПСр-15 silver

spelter), which provides for good electrical contact and high mechanical strength of the joint.

In electric brazing (Fig. 6.17), the prepared lap-joint *2* of the conductors to be connected is clamped between carbon electrodes *3* which are supplied with a voltage of 6 to 12 V via a switch *4* (a foot-pedal switch). Upon completing the circuit by the switch, a current starts flowing through the joint and the carbons. Since the resistance of the carbon electrodes is high, they become heated and in turn heat the joint. As soon as the joint is raised to the melting point

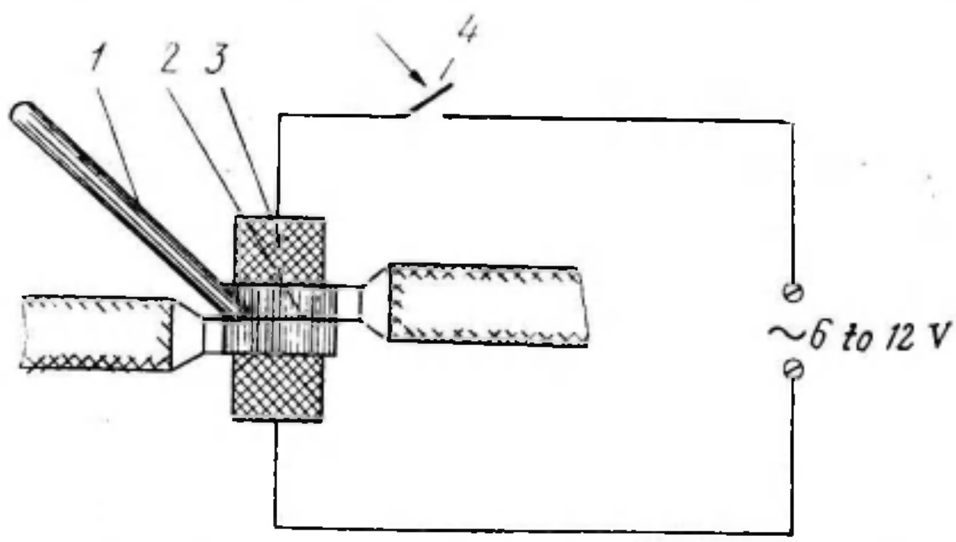


Fig. 6.17. Schematic diagram of electric (resistance) brazing of conductors

of spelter, a spelter stick *1* is brought into contact with the edges of the heated conductors and, as a result, spelter melts and fills up the gap between the conductors. Then the current is switched off, the joint cools down, and spelter solidifies, thus firmly joining the conductors.

Aluminium conductors are connected to one another or to copper conductors by argon-arc or cold welding, rather than by soldering (soldering does not provide for the requisite quality of connection). In cold welding, the conductors to be joined are butted and compressed by means of a special press. At that time the molecules of one metal at the boundary layer between the conductors enter the other metal and the conductors thus become joined. The mechanical strength of the joint obtained in this way is equivalent to that of the solid conductor.

Electric Brazing of Copper Leads with Phosphorous-Copper Spelters. Prior to brazing, the leads are installed in place

on the core-coil unit and their ends are dressed. If old leads are used, their ends are filed bright and then the leads are fixed in place with beechwood cleats according to markings.

If new leads are to be used, the lead blanks are cut off with special shears, a hacksaw, or a chisel. Then the blanks are bent to the required shape, tried in their place by putting them to the cleats, and the ends to be joined are fitted together. The ends must be overlapped for a distance of

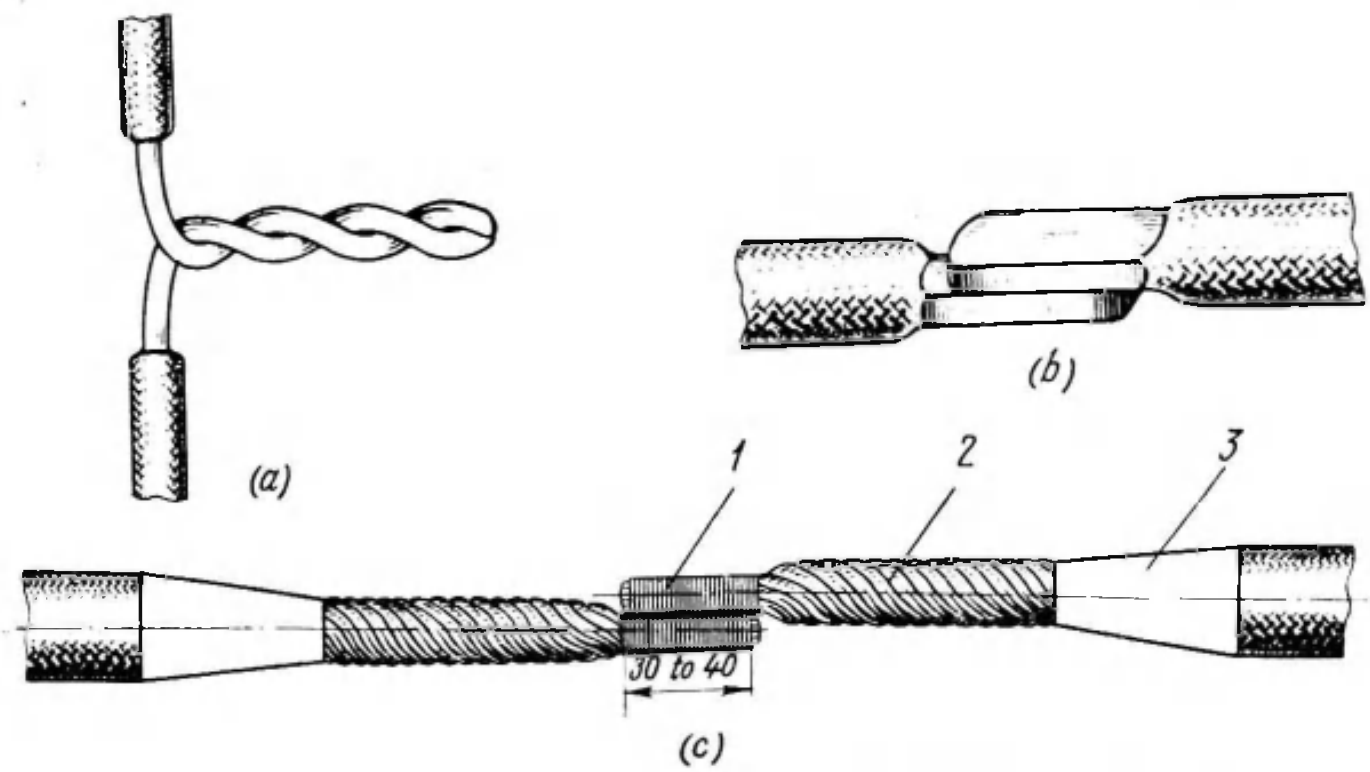


Fig. 6.18. Preparation of the ends of conductors for electric brazing

(a) light conductors; (b) heavy conductors; (c) flexible conductors; 1—flattened and bound end of conductor; 2—conductor; 3—conductor insulation

30 to 40 mm. Rigid leads (made from flat or round bars) are bent and cut off finally before fastening them with cleats, while flexible leads (made from Grade ПБОТ cable) are first fastened with cleats and then bent in position. The ends of the leads and windings are skinned with a knife so that their insulation tapers off toward the joint.

Skinned ends of fine round wires are cleaned from varnish insulation with a knife and emery paper and tightly twisted together as shown in Fig. 6.18*a*, using combination pliers. The ends of heavy round wires are flattened, filed with a flat file to remove irregularities and sharp corners, and then put together flatwise (Fig. 6.18*b*).

The ends of flexible leads made of Grade ПБОТ cable consisting of a large number of copper wires are bound over a length of 30 to 40 mm with a fine copper wire (usually one of the wires of the cable itself). The bound section of the lead is flattened, while its unbound end is cut off at a distance of 3 to 4 mm from the binding. The lead ends thus prepared are then lapped flatwise (Fig. 6.18*c*).

The binding of the end of a flexible lead when preparing it for electric brazing is illustrated in Fig. 6.19. Lead ends

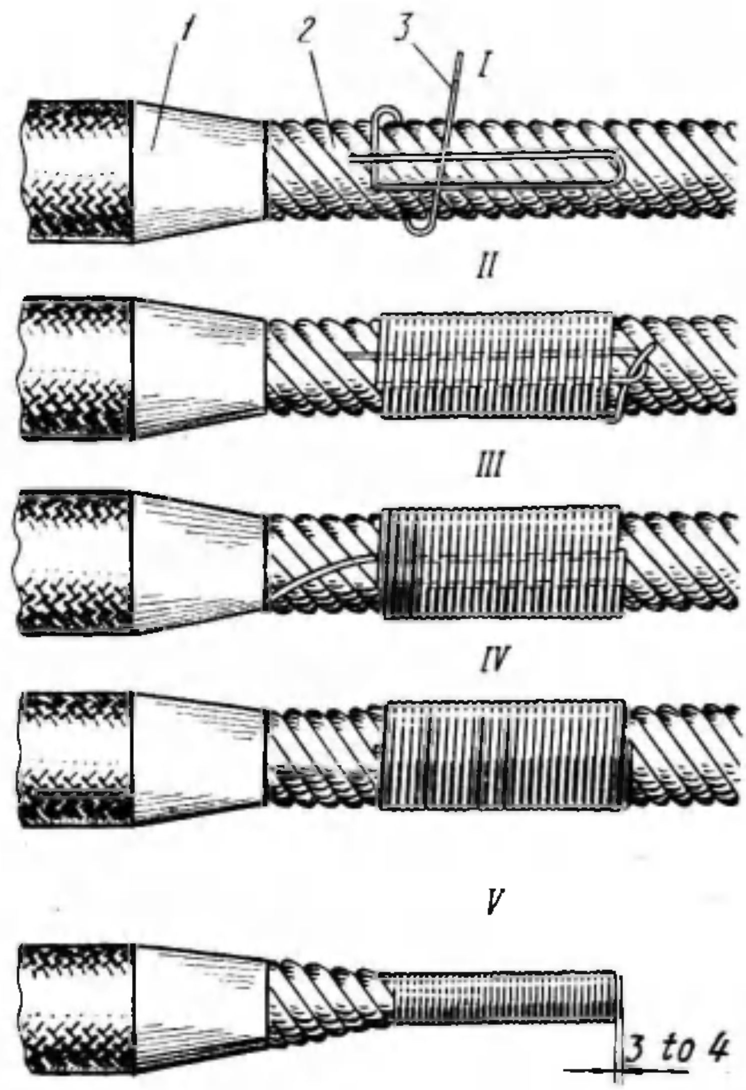


Fig. 6.19. Binding the end of a flexible conductor

I—making a loop; *II*—wrapping the binding wire and passing its finish into the loop; *III*—pulling the finish of the binding wire under the binding; *IV*—cutting the start of the binding wire; *V*—cutting and flattening the end of the conductor

are flattened on a steel plate by tapping a hammer against the binding so as not to break the binding wire and individual wires of the lead. The thickness of the flattened end must be nearly equal to half the cable diameter.

When it is necessary to connect a flexible lead to an end of a winding wound with several parallel conductors *2* of rectangular section (Fig. 6.20), the conductors are laid around the binding *1* of the lead end as shown in Fig. 6.20*a*.

If the number of the parallel conductors in the winding is too great, two or more flexible leads are used.

It is more troublesome to prepare for brazing and to braze heavy bar leads when connecting them to the ends of windings wound with a large number of parallel conductors. Since such joints are difficult to heat during brazing, the ends of the bar leads are split into separate elements. Slits *5* (Fig. 6.20*b*) are cut at the end *3* of a bar lead and the parallel conductors *4* of the winding end are distributed among the

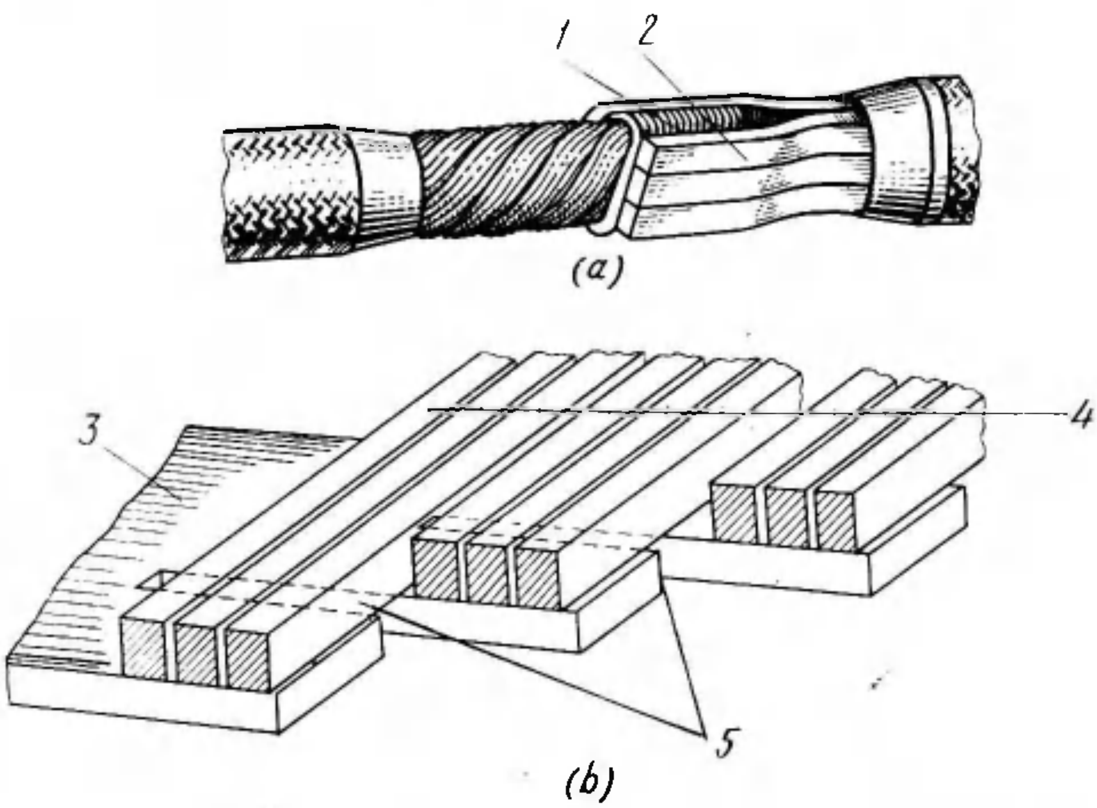


Fig. 6.20. Methods of connecting heavy leads to the ends of windings wound with several parallel conductors

(*a*) connecting a flexible lead; (*b*) connecting a bar lead

separate elements of the lead end. The winding conductors are placed on the bar lead either edgewise or flatwise. To prevent the elements of the prepared joint from being moved apart, they are temporarily fastened with fine wires which are removed after brazing.

After all the joints of the HV and LV leads have been prepared for brazing, electrical tests are carried out with a view to determining the phase-displacement group of the winding connection and the transformation ratio. Then the necessary tools and devices are prepared and the lead joints are brazed one after another.

The following devices, tools and materials are used in electric brazing: an electric-brazing apparatus with a voltage of 6 to 12 V on the LV side, portable electric-brazing tongs equipped with carbon electrodes, a foot-pedal switch

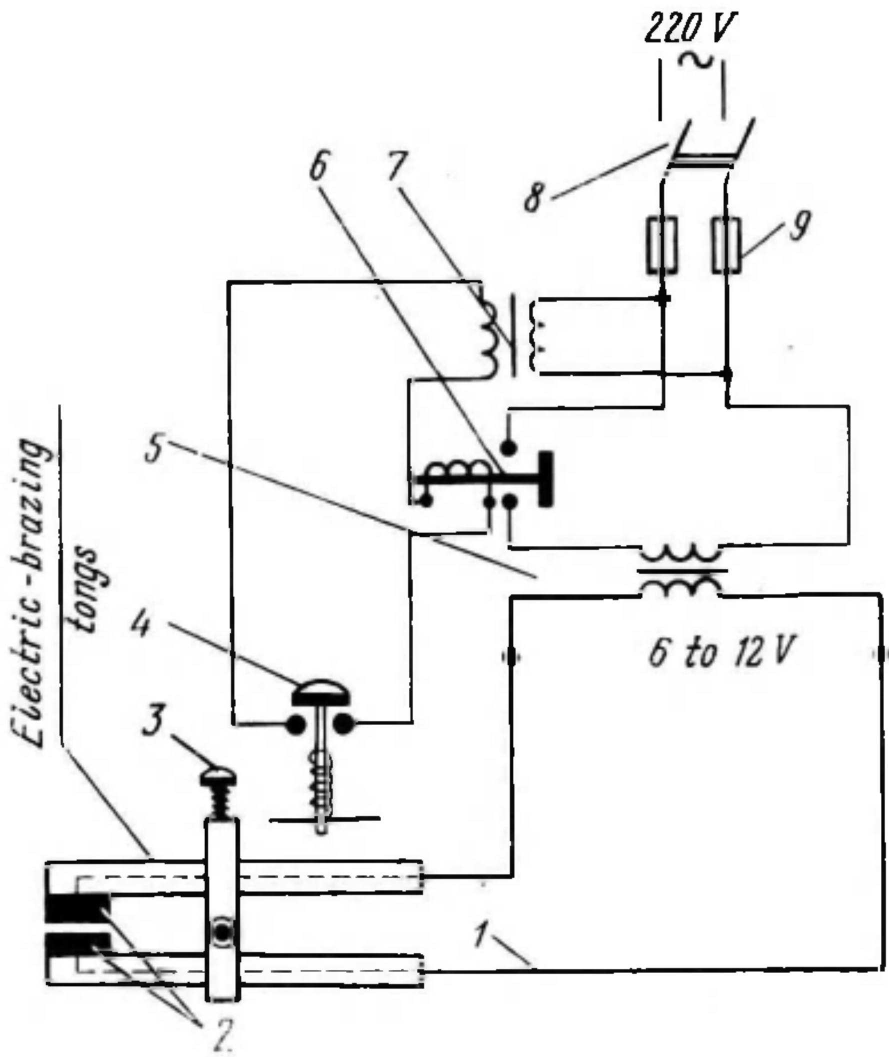


Fig. 6.21. Circuit diagram of an electric-brazing apparatus

for periodically switching current on and off, a file, a bench bammer, a knife, and spelter sticks, usually measuring 3 mm by 8 mm by 200 mm.

An ordinary welding transformer may sometimes be used for electric brazing. For this purpose, an LV winding of flexible insulated wire is wound around the outer coil of the transformer. Since the voltage per turn in welding transformers is 2 to 3 V, the voltage required for electric brazing (6 to 12 V) can be obtained by winding 3 to 4 turns. If necessary, extra turns can be added or surplus turns removed.

The joint to be brazed is heated by means of portable electric-brazing tongs with carbon electrodes *2* (Fig. 6.21). The halves of the tongs are insulated from each other and

are hinged on a pin. Flexible cables *1* connect the tongs to the LV side of a brazing transformer *5* whose primary is connected to 220- or 380-V mains (depending on the voltage rating of the transformer) via a knife switch *8*, fuses *9* and a magnetic contactor *6*. The supply circuit of the contactor coil is completed by a foot-pedal switch *4* which serves to switch the brazing transformer in and out. For safety reasons, the foot-pedal switch operates on a voltage of not higher than 36 V, which is supplied from a separate transformer *7*.

For brazing, the prepared joint is clamped between the carbon electrodes of the tongs by a screw clamp *3*, the pedal is depressed, and the joint is heated until it becomes red hot. If a bright glow appears at the points of contact of the carbons, current should be switched off and the joint should be clamped more tightly. Then a spelter stick is brought into contact with the edges of the heated conductors to be joined; spelter melts and fills up the gap between the conductors. If spelter does not melt and sticks to the joint, heating should be continued. The heating temperature is controlled by switching current on and off periodically for short periods of time.

Electric brazing should be done as quickly as possible, so as to avoid the burning-out of phosphorus that protects the joint against oxidation. As soon as the gap between the conductors is filled up with spelter around the entire perimeter of the joint and the ends of flexible conductors are impregnated with it, current is to be switched off. After spelter has solidified (darkened), the joint is released from the tongs and carefully inspected. It must be well brazed round without gaps and must be free from blisters and burnt-out spots. Inaccessible portions of the joint can be inspected with a pocket mirror placed behind the joint. Then the joint is filed on all sides to remove sharp corners, spelter runs, and irregularities.

Successive application in the field have found portable electric-brazing machines, Model ЭПАМ-1 for 2 000 A (Fig. 6.22) and Model ЭПАМ-2 for 4 000 A. The use of these machines relieves one from the burden of preparatory work involved in finding in each particular case a suitable transformer and control equipment and putting them toge-

ther to obtain a brazing apparatus, and provides for electrical safety in operation. These machines are equipped with water-cooled electric-brazing tongs *2* which increase the productivity of labour and protect operators from burns. The machines are mounted on castors and their cabinets

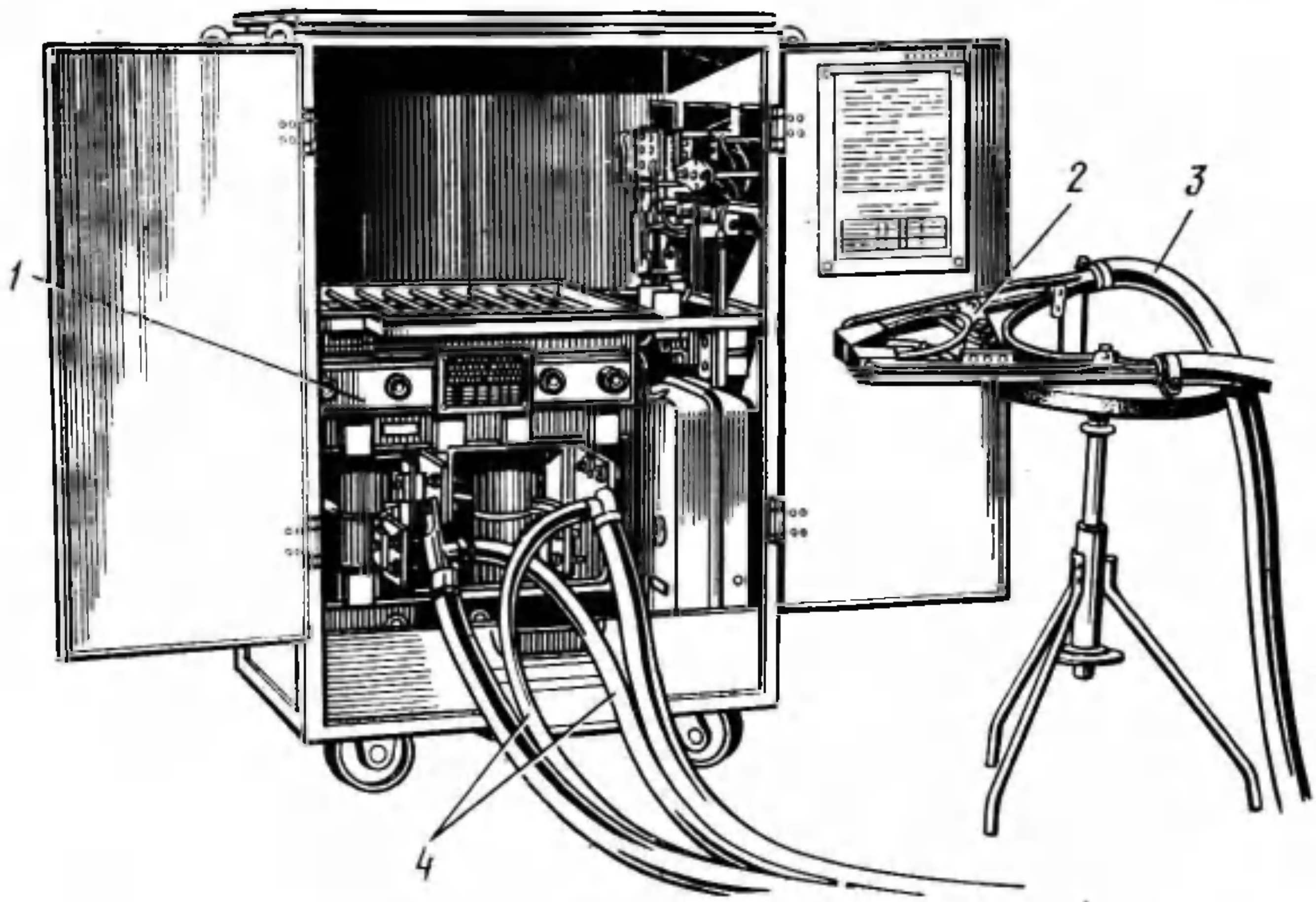


Fig. 6.22. Model ЭПАМ-1 electric-brazing machine

1—transformer with control equipment; *2*—electric-brazing tongs; *3*—water-cooled conductors; *4*—water hoze

are provided with handles and lifting lugs so that they can be easily moved about the repair grounds and handled in shipment.

Electric brazing with phosphorous-copper spelters is not very difficult an operation, but it requires practical skills to carry out properly. In electric brazing, one should strictly adhere to fire prevention regulations, especially when brazing leads that have already been in operation and hence, have their insulation impregnated with transformer oil. To prevent the transfer of heat from the heated joint to the insulated portions of the lead and winding conductors, the bare portions of the conductors on both sides of the joint should be coated with a wet asbestos paste. Molten spelter must not

get onto the oil-impregnated components near by, therefore, sheets of asbestos should be placed under the joints being brazed. In addition, near the workplace there must be a fire extinguisher, a box with sand, a shovel, and a bucket with water.

Welding of Aluminium Conductors. High-quality joints of aluminium leads are produced by argon-arc welding, resistance welding, and sometimes, by gas welding. The argon tungsten-arc welding method has proven most perfect. To obtain an electric arc in the atmosphere of an inert gas—argon—a voltage from a welding transformer equipped with an oscillator is applied across a tungsten electrode placed in an argon torch and the wires to be welded. The welding current is set at 100 to 130 A by means of a current regulator. The torch is fed with argon from a cylinder via a pressure regulator with an output pressure of about 0.1×10^5 Pa.

After the welding circuit is completed, a valve is opened to let argon into the torch which is then brought to the joint to be welded and the tungsten electrode is touched to the wires. At that time an arc strikes between the electrode and the joint, which fuses off the wires at the joint and an aluminium welding stick whose metal partially fills and smoothes out the weld. Argon gas protects the metal against oxidation. Model ПШП-10 welders using a consumable electrode—an aluminium wire—which is automatically fed to the weld, are widely employed for D.C. argon-arc welding of aluminium wires.

Tinning and Soldering of Copper Lead Connections with Tin-Base Solders. As compared with electric brazing with phosphorous-copper spelters, soft soldering with tin-base solders suffers from a number of essential drawbacks: low mechanical strength and thermal stability and relatively high resistance of the joints produced and high cost of solder. Therefore, soft soldering is only used where electric brazing cannot be employed.

Soldering is done with a soldering iron or blowlamp, using Grade ПОС-40 solder and rosin as a flux.

When soldering wires of large section, their ends are preliminarily tinned and then inserted into a tinned copper or brass sleeve *2* with an opening (Fig. 6.23) or a binding clip. The joint is heated with a blowlamp *5*. The opening in the

sleeve is first filled with rosin *4* and then a solder stick *3* is touched to the heated portion of the wires *1* to be joined and melted into the sleeve until the gap between the sleeve and the wires is filled up with solder. It is impermissible

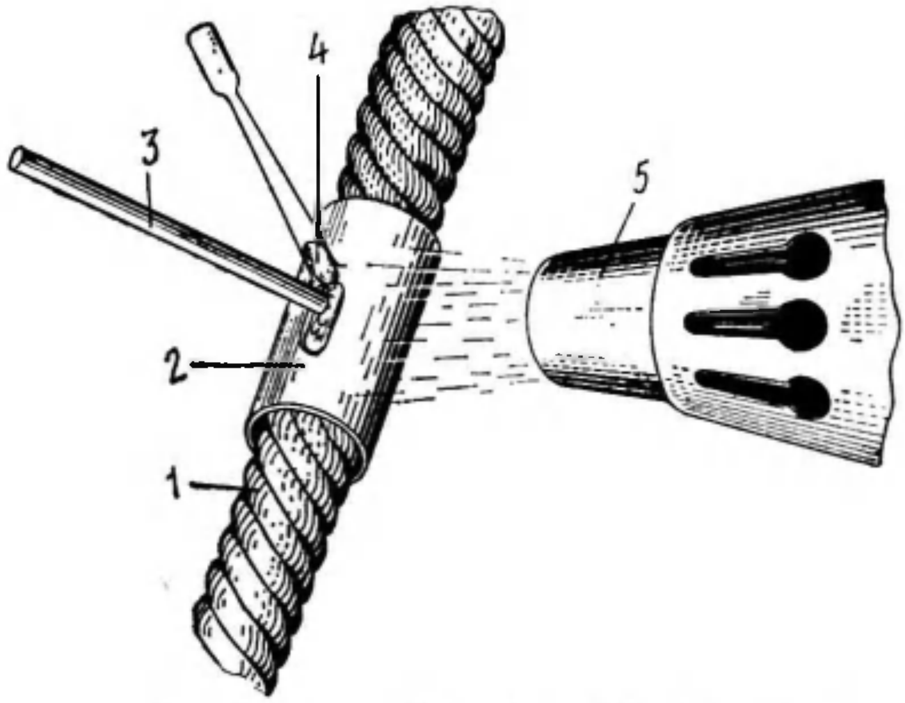


Fig. 6.23. Soft soldering of leads with the use of a sleeve

to heat and melt solder by flame. To make the joint surface even and smooth, the joint is wiped with a piece of clean cloth before soldering is ended.

Insulating and Fastening the Leads

After soldering, the lead connections are insulated. First, strips of varnished cloth and crepe or cable paper and linen-finished tape are prepared, their width (20 to 40 mm) depending on the size of the leads. Crepe paper is cut into strips across crinkles on a paper-cutting machine or a special device. Varnished cloth is cut along the diagonal of yarn. For this purpose, pieces 1 to 1.5 m long are cut off from a roll and coiled into tubes 20 to 30 mm in diameter, which are then cut into strips with bench shears. Before insulating the lead connections, burnt insulation on the leads is tapered off toward the joints so that the length of the tapered portions is ten times the lead insulation thickness on one side.

The lead connections are insulated manually by applying half-lap layers upon layers of insulating strips until the

thickness of the main lead insulation is reached (Fig. 6.24). When doing this, the strips are tensioned and smoothed by hand in the winding direction so as to ensure that the layers are applied tightly without any folds and voids between them. For mechanical protection, one layer of half-lapped linen-finished tape is applied over the main insulation.

The lead connections being insulated, the leads are additionally insulated at places where they pass between their support cleats by applying strips of cable paper or roll pressboard in concentric layers until the required thickness

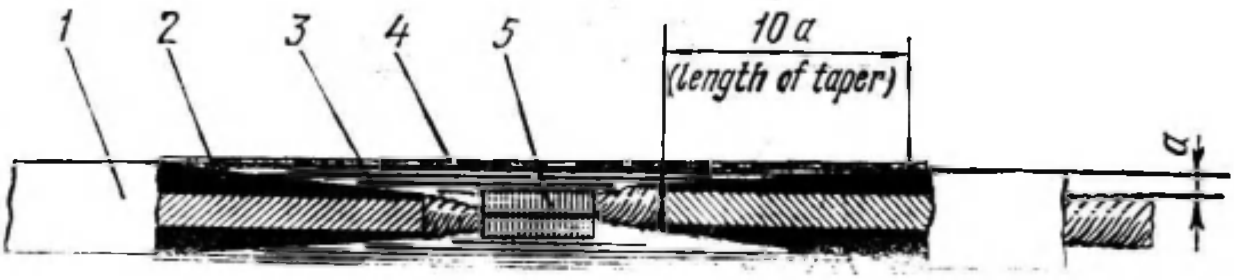


Fig. 6.24. Insulating a soldered connection of a lead

1—lead end; *2*—tapered end insulation; *3*—insulation of varnished-cloth strips applied half-lap; *4*—insulation of linen-finished tape applied half-lap; *5*—soldered connection; *a*—one-side insulation thickness of the lead

is obtained. The strips for additional insulation must be cut wide enough to ensure that it projects beyond the cleats on both sides for at least 25 mm at a voltage of 35 kV and for 75 mm at a voltage of 110 kV.

In size I and II transformers, the LV leads and their connections are usually not insulated, while the HV leads are insulated with paper-base laminate tubes. The joints between separate tubes are insulated with varnished cloth or crepe paper. These joints must not get between the lead-support cleats and, when on adjacent leads, must be displaced not less than 30 mm relative to one another.

The insulated leads are clamped in the support cleats and the core-coil assembly is subjected to electrical tests after all its screw fastenings have been finally tightened.

6.11. Drying Out, Inspecting, and Assembling Transformers

After it has been assembled and tested, the core-coil unit is dried out. The physical essence of the drying-out process consists in that on heating the insulation, the

moisture contained in the material moves from its internal pores to the surface, from whence it goes into the surroundings. The transfer of moisture is due to the difference in temperature between adjacent layers of insulation, as a result of which moisture is driven off from the more heated layers and goes to the less heated ones. This is explained by the fact that, according to the temperatures, the pressure of water vapour over the surface of the material is lower than that in its outer layers, so moisture moves from places where the so-called partial pressure is higher to places where it is lower.

Therefore, when drying out, it is essential to raise the vapour pressure in the layers of insulation and to keep it down in the surroundings. The first requirement is satisfied by heating the insulation and the second, by maintaining a vacuum in the drying oven or in the tank where the drying-out takes place. In repair practice, transformers of up to Size III inclusive and some Size IV transformers are dried out without vacuum. To produce the required vapour pressure differential, the heating of the insulation in the course of the drying-out process is periodically interrupted and the outer surface of the core-coil unit is sharply cooled with a jet of clean, cold air. The process of accelerating the drying-out by producing a temperature differential is based on the phenomenon of thermal diffusion.

The main characteristics describing the drying-out process are the insulation resistance and the heating temperature. During drying-out, the core-coil assembly is heated to a temperature of 95 to 105°C which is then maintained at a constant level as far as possible. Heating to a higher temperature is impermissible, since this will cause deterioration of properties of the insulation and its eventual failure. In the course of drying-out, the temperature is measured at several most characteristic points.

The process of moisture removal in drying-out is characterised by the curve depicting the change of the insulation resistance in time at a constant temperature. At the beginning of the drying-out operation the insulation resistance sharply drops and then remains almost constant during 5 to 8 hours. As the moisture is driven off, the insulation resistance rises and by the end of the drying-out, it becomes

sustained at a certain definite value specific to the given type of transformer. The drying-out is considered to be completed if at the end of the process the insulation resistance of the transformer windings at the highest steady temperature remains unchanged during 5 to 6 hours.

In the course of drying-out, the insulation resistance is measured by means of megohmmeters operating at voltages of 1 000 and 2 500 V, the former being used to measure resistances below 100 MΩ and the latter, those of 100 MΩ and over. The insulation resistance and temperature are recorded hourly in a special register.

Methods of Drying Out Without Vacuum

Depending on the actual repair conditions and available equipment, various methods for drying out the core-coil assembly of transformers may be used. Let us consider some methods using no vacuum.

Drying Out by Induction Method. This method is widely used in repair practice for drying out medium- and large-size transformers under actual service conditions. By this method, the core-coil assembly is placed in a tank with a magnetizing coil wound around its perimeter on the outside (Fig. 6.25). The coil is supplied with an A.C. current and produces a magnetic flux which has its path through the steel walls of the tank and induces eddy currents in them. These currents heat the tank, and from the tank heat is transferred to the core-coil assembly *1*. Usually, the tank of the transformer itself is used for the purpose.

To improve the heat conservation ability of the tank, it is blanketed with asbestos cloth *3*. The magnetizing coil *2* of insulated wire is wound directly around the thermal insulation blanket. If a bare wire is used for the coil, the wire is then secured to wooden strips arranged vertically around the periphery of the tank. The necessary number of turns in the coil and the size of its wire are determined approximately by calculations. The final number of turns is ascertained in the course of heating and, if necessary, some extra turns may be added or surplus turns removed.

To provide for uniform heating of the core-coil assembly, the turns of the coil are so arranged on the tank that 60

to 70% of their total number fall on its lower half. At the very bottom of the tank and at its top the turns are wound as close as possible to one another. The tank should be wiped dry before placing the core-coil assembly into it. To avoid condensation of water vapours, the tank bottom should be heated and its cover blanketed to the best of one's abilities. For safety reasons, the tank should be earthed (jumper *5*).

For ventilation, a vent pipe *4* 1.5 to 2 m high is installed on the tank cover and one of the openings at the tank bottom

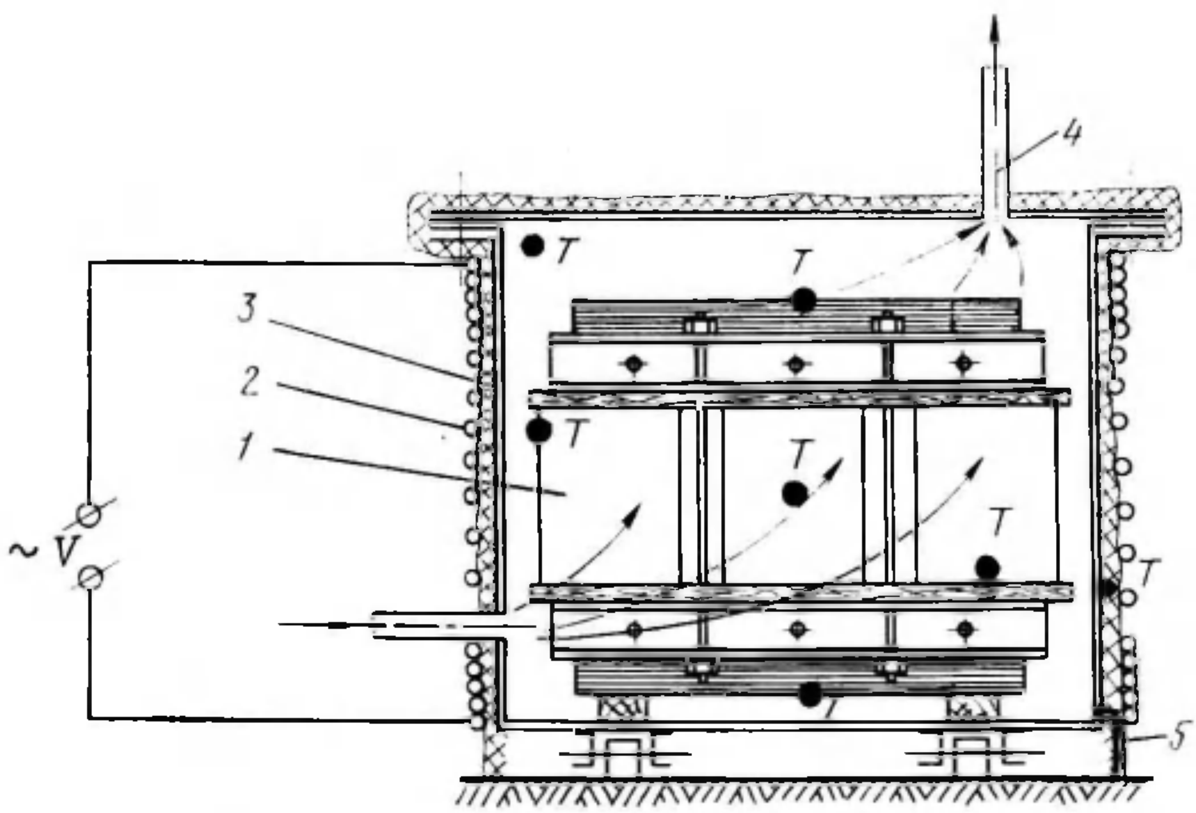


Fig. 6.25. Drying out a transformer in its own tank by induction method without vacuum

is held open. The pipe is blanketed with asbestos cloth. A most effective means for removing moist air from the tank is the use of an exhaust fan on one of the openings in the tank cover. Favourable conditions for thermal diffusion to take place are provided by operating the fan periodically.

When drying out without vacuum, the heating temperature is controlled by means of thermocouples embedded in the transformer windings and yokes and fitted on the tank walls. The temperature of the windings is maintained within 95 to 105°C, while that of the tank walls, within 110 to

130°C, depending on the distance between the tank walls and the windings.

Transformers are dried twenty four hours a day without interruption, and all thermocouple and megohmmeter readings are entered in the register every hour. The insulation resistance is measured between the HV, MV and LV windings and the tank (earth) and also between each of the windings and the tank, the other windings being earthed. Once the drying-out is ended, heating is ceased and the core-coil assembly is cooled to a temperature of 60 to 70°C and then covered with oil.

The drying-out entails substantial shrinkage of the transformer insulation and hence, the loosening of the windings, leads, and other units. Therefore, the core-coil unit, after it has been dried out and impregnated with oil, is removed from the tank for inspection. The windings are packed out and all the nuts on the clamping studs, tie-rods, lead support cleats, tap-changer, etc. are tightened up and locked. After that, the rubber sealing gasket of the tank cover is replaced and the transformer is assembled in the usual way.

Drying Out in an Oven. The core-coil assembly is placed in a drying oven where it is dried out in the usual manner. This method is mainly used at manufacturing and repair plants. Small ovens available on the spot may be used for drying out comparatively small transformers, usually not over 630 kV A in capacity. Drying ovens may be heated by electric heaters, steam or hot air and blanketed with asbestos or some other refractory heat-insulating material.

Drying Out by Infrared Rays. In this method, use is made either of special infrared lamps which are capable of transforming 80 to 90% of the input electrical energy into radiant heat energy, or of special heaters.

Heat from the lamps is transferred by radiation, therefore to direct the heat flux onto the core-coil assembly, the lamps are placed in reflectors and mounted on supports at a distance of 300 mm from the core-coil assembly in such a manner, as to ensure that the rays are uniformly spread over its entire surface.

This method may be used for drying out transformers of up to 1 000 kV A.

Temperature Measurement

When drying out transformers, the temperature of individual components of the core-coil assembly is measured by means of thermometers, temperature indicators, and thermocouples, the latter being most widely used in repair practice. A thermocouple consists of a pair of wires of dissimilar metals joined at each end. One junction (hot) is at the point where the temperature is to be measured and the other (cold) is kept at a lower fixed temperature. Owing to this difference in temperature between the junctions, a thermal emf is generated, causing an electric current to flow in the circuit. This current can be measured by means of a galvanometer in the circuit, or the thermal emf can be measured using a potentiometer. The wires are usually from 0.5 to 1 mm in diameter and are usually joined at the end which is exposed to the temperature to be measured, the other ends being free to connect to an instrument for measuring the emf, whose scale is graduated to read temperatures in degrees Celsius. The hot junction is made in the form of a bead by welding or soldering and the wires are insulated from each other. Different combinations of metals produce different emf's for the same temperature intervals, their absolute value ranging from 3 to 7 mV for a temperature difference of 100 deg C.

The greatest thermal emf's for a temperature difference of 100 deg C are produced by thermocouples of the following combinations of conductor materials: chromel-copel (6.95 mV), iron-copel (5.75 mV), chromel-alumel (4.1 mV), and copper-constantan (4 mV).

The copper-constantan type of thermocouple, unlike others, permits its hot junction to be obtained by soft soldering with Grade ПОС-40 solder, this being of great advantage since in repair practice, thermocouples are, as a rule, made by repairmen themselves.

Preparation for Drying-Out and Drying-Out Conditions

If it is contemplated to dry out the core-coil assembly of a transformer in its own tank, two or three terminal bushings are then mounted on the tank cover, their number depending

on the number of the windings in the transformer (HV and LV windings or HV, MV, and LV windings). A lead from each of the windings is connected to its respective bushing, and thermocouples are fitted at the requisite spots on the windings, core, and tank walls. The connecting wires from the thermocouples are brought out through one of the free openings in the tank cover and connected via a selector switch to a galvanometer set up on the desk of the man on duty in charge of the drying-out. The wires must not touch the current-carrying parts and the body of the transformer. Where they pass through the opening of the cover, the wires are spread apart and clamped between rubber packings.

All the openings but one (for mounting a vent pipe) in the cover are closed with blind flanges. Then the core-coil assembly is slinged and put in the tank for drying out, the tank being preliminarily wiped dry, and the tank cover is sealed off and secured in place. The tank is blanketed with asbestos cloth or with mats of some other heat-resistant material and then the magnetizing coil is wound around it.

To measure the insulation resistance of the windings, well-insulated leads are brought from the terminal bushings mounted on the tank cover and from the tank to the desk of the man on duty.

Then the tank is earthed and the drying-out is commenced by switching in the magnetizing coil.

The man in charge of the drying-out must have on his desk the drying-out instructions manual and register, as well as a clock, megohmmeters, and instruments for monitoring current and voltage.

So long as the core-coil assembly is being heated up to a temperature of 70 to 80°C the opening for exhausting moist air is held closed, then it is opened and a vent pipe is installed on it and one of the openings at the bottom of the tank is opened to provide for natural ventilation.

Accident and Fire Safety

The drying-out of transformers involves the use of supply voltages ranging from 120 to 380 V, and some parts of transformers are heated in the process to as high a temperature

as 120 to 130°C. Therefore, to provide for accident and fire safety, the following rules must be strictly adhered to.

1. The transformer tank and electrical equipment cabinets must be earthed.

2. Electric wiring must have good insulation and reliable connections.

3. The area where the actual drying-out takes place must be fenced in (usually by means of hemp-rope barriers) and must be provided with warning signs bearing an inscription "CAUTION! LIVE EQUIPMENT".

4. The room where the transformer is to be dried out must be well ventilated and must be provided with means for fighting fire, such as a box with sand, shovels, and fire extinguishers.

5. One must neither smoke nor use open fire in the room where the transformer is being dried out.

6. The man on duty must stay close to the transformer and must never leave it unattended.

7. The tanks and ovens used for drying out transformers must be provided with exhaust ventilation means that must rule out any possibility of explosion-hazard concentration of oil vapours.

8. The use of open-coil electric heaters for heating up the tank bottom is prohibited.

Assembling the Transformer After Drying-Out

The drying-out being ended, the magnetizing coil is switched out, the core-coil unit is allowed to cool down to a temperature of 70 to 80°C, and the tank is then filled through the top valve with dry transformer oil cleaned from mechanical impurities, the oil being raised to a level at which it fully covers the core-coil unit. Before filling the tank, the oil should be subjected to a breakdown test and a brief chemical analysis to make sure that it complies with the relevant standards.

The core-coil unit is kept covered with oil for a sufficient period of time for it to become impregnated with oil, the length of this period depending on the capacity and class of insulation of the transformer, and then it is slinged and pulled out of the tank for inspection. The scope of work invol-

ved in this inspection is the same as in any medium repair. Special attention is given to the clamping of the windings. As a rule, the windings are packed out and insulation is added, if necessary. Then all the fastenings are tightened up, the tap-changer contacts are checked, and the insulation resistance of the clamping studs is measured.

After that, the tank cover is made complete with all the fittings and the lifting rods are sealed off in the cover. The tank is carefully cleaned to remove all sediment and dirt, the core-coil assembly is lifted and placed in the tank and then covered with oil, using a filter press or centrifugal oil purifier. Then the transformer is finally assembled (see Sec. 5.9) and tested for leak tightness after oil has been added to capacity. The oil is allowed to settle for 8 to 10 hours and then the transformer is subjected to electrical tests.

6.12. Specific Features of Drying Out and Repairing Transformers for 110 kV and Upwards

Drying Out Transformers

During repair, large power transformers are dried out by induction method in their own tanks under a vacuum of 5 to 10 mm mercury. In addition to the above-described preparatory work, vacuum drying-out involves some specific operations, such as hermetic sealing of the tank and testing it for vacuum tightness, and putting together the vacuum-drying and filling equipment. Vacuum drying-out ensures thorough removal of moisture and air inclusions from insulation. When impregnated with oil, such insulation possesses high electric strength.

The tank is tested for vacuum tightness as follows. A vacuum pump is connected to one of the top valves on the transformer, and then the tank is tightly sealed and evacuated to a pressure indicated in the transformer specifications, the pressure in the tank being gradually reduced in steps of 100 mm mercury every 15 minutes. If there are no such data in the transformer specifications, one may proceed from the following figures: transformers for 110 to 150 kV are evacuated to 350 mm mercury and those for 220 to

500 kV, to 10 or 15 mm mercury. Then the valve on the vacuum line is closed, the pump is stopped, and the pressure in the tank is measured twice and recorded in a register, the first measurement being taken immediately after the pump has been stopped and the second, in one hour.

The tank is considered to be vacuum-tight if the inleakage for an interval of one hour does not exceed 20 mm mercury. If the inleakage is greater, the leak should be detected and eliminated, and then the tank should be tested for vacuum tightness once more.

After testing, the tank is blanketed with asbestos cloth applied in two to three layers, depending on the thickness of the material. The thickness of the heat insulation should be 10 to 15 mm on the tank walls and 15 to 20 mm on the cover. The vertical stiffening bars are not blanketed, because they are heated 30 to 40 deg C above the temperature of the tank walls.

Then a three-phase magnetizing coil is wound around the tank. The entire coil is wound in the same direction, so to change the direction of current in the phase arranged in the middle of the tank, this group of turns is connected in opposition. Additional heaters, preferably of the steam tube type, are installed under the tank bottom, the required number of such heaters being determined by calculation. The tank and electrical equipment housings and cabinets are earthed. Then the insulation resistance of the magnetizing coil, resistance heaters, and power-supply equipment is measured with a megohmmeter, the entire electrical system is checked, and the drying-out is started.

Figure 6.26 illustrates schematically the vacuum drying-out of transformers of 110 kV and over by induction method. An A.C. voltage is applied to a three-phase magnetizing coil *2* wound around a heat-insulated transformer tank *3* connected to earth *1*. The tank cover is equipped with a vacuum meter *4* with the 0-760 mm mercury range and temporary terminal bushings *7* connected to the HV, MV, and LV windings. Wires *6* from thermocouples fitted inside the tank are brought out through one of the openings in the cover where they are sealed with rubber packings. A vacuum line *8* for evacuating the tank and an oil line *5* for filling it with oil are connected to two top valves on the transformer.

Closed-type resistance heaters *16* are installed under the tank bottom.

A container *17* provided with three valves, *a*, *b*, and *c*, is connected to the oil drain of the tank and serves to remove oil residues from the tank during drying-out. Normally, all the three valves are closed. To drain oil from the tank and into the container, the valve *a* is opened, and to drain it from the container, the valve *a* is first closed and then the

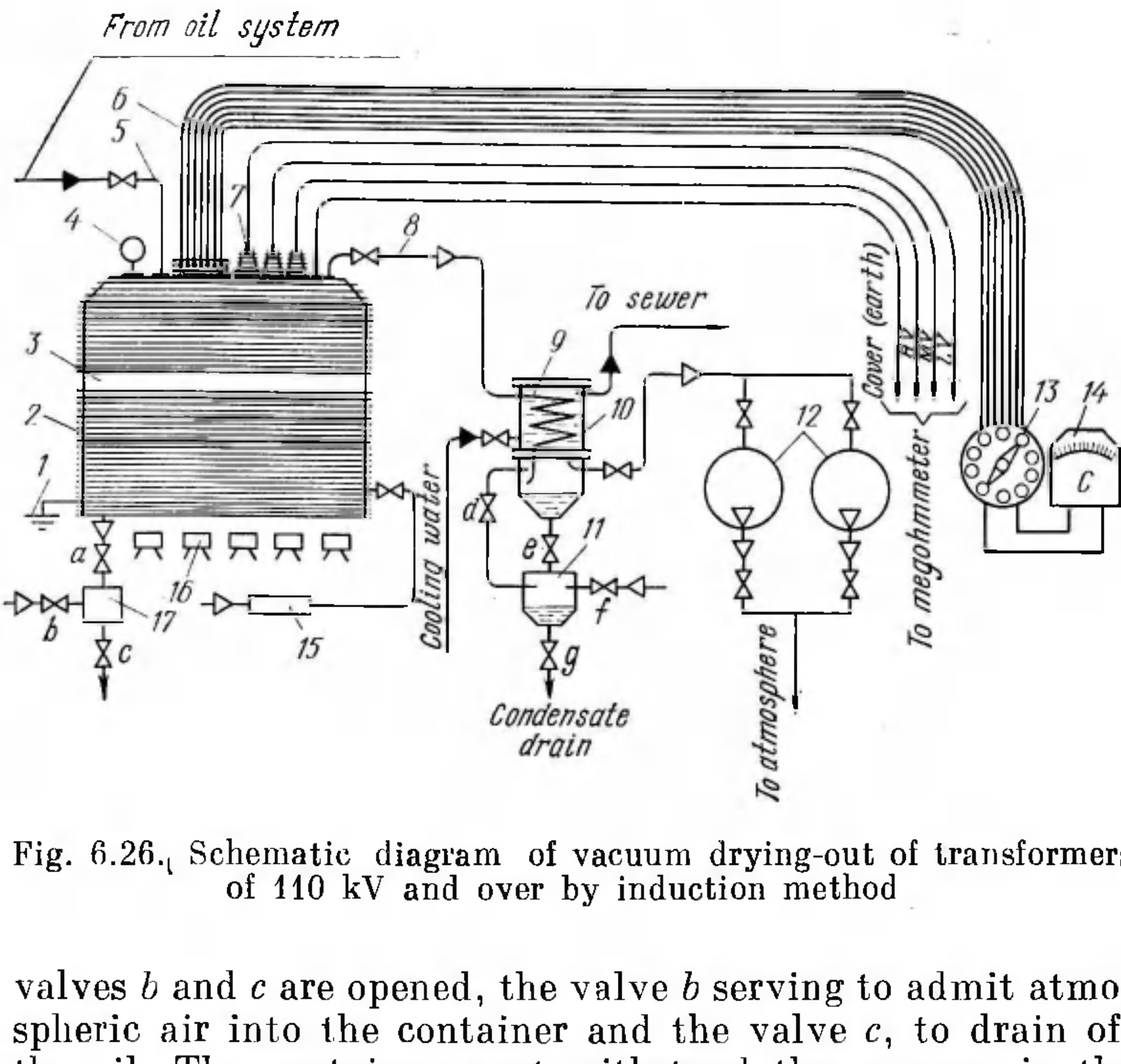


Fig. 6.26. Schematic diagram of vacuum drying-out of transformers of 110 kV and over by induction method

valves *b* and *c* are opened, the valve *b* serving to admit atmospheric air into the container and the valve *c*, to drain off the oil. The container must withstand the vacuum in the tank. For convenience in handling it when periodically draining off the oil and for fire safety reasons, the container is set up at a distance of 1.5 to 2 m from the transformer tank.

The air admitted into the tank is cleaned by means of a filter *15* connected to one of the side valves on the transformer. The filter is a metal vessel 5 to 6 l in capacity filled

with glass wool. The air freely enters the filter through a metal gauze in the intake pipe.

Two vacuum pumps *12* (one of them being a stand-by) are used to evacuate the tank. In repair practice, transformers of up to 40 000 kV A are vacuum dried with the aid of Model BH-4r vacuum pumps, while those of larger size are dried using Models BH-6r and BH-300 pumps. To condense water vapours and protect the vacuum pumps against overheating, use is made of a coil condenser *10* which is inserted in the vacuum line between the tank and the pumps. The condenser must withstand the vacuum in the tank and its throughput capacity must match the discharge of the pump.

The condenser operates as follows. The moist air pumped out of the tank enters the coil *9* of the condenser, where water vapours are condensed owing to the coil being cooled with water from outside. The cooling of the coil is improved by using the countercurrent principle (the cooling water enters the condenser jacket at the bottom and leaves it at the top, while the moist air flows through the coil in the opposite direction). The condensate is separated from the air in the lower compartment of the condenser. The condensate settles down, while the air goes to the pump that exhausts it into the atmosphere.

The condensate is drained off through an intermediate vessel *11* as follows. With the valves *e*, *f*, and *g* being closed, the valve *d* is opened to equalize the pressure in the lower compartment of the condenser and in the vessel. Then the valve *e* is opened to let the condensate into the vessel. After that, the valves *d* and *e* are closed, the valve *f* is opened to admit atmospheric air into the vessel, and then the valve *g* is opened and the condensate is drained off.

To monitor the drying-out conditions and take the necessary measurements, a round-the-clock watch should be organized. On the desk of the man on duty there must be megohmmeters for 1 000 and 2 500 V, a clock, a selector switch *13* to connect in turn the thermocouples fitted in the tank to a galvanometer *14* graduated to read temperatures, the ends of the leads connected to the temporary terminal bushings for measuring the insulation resistance of the windings, a vessel for collecting condensate and measuring its amount,

a telephone set for communicating with a fire brigade and a medical station, and the drying-out register and instructions manual. During the entire drying-out period — from the moment the magnetizing coil is energized and till the end of impregnation of the core-coil unit with oil—the man on duty must hourly enter in the register the time, temperature, insulation resistance, pressure in the tank, and the amount of condensate collected.

The procedures to be followed when drying out the core-coil unit and impregnating it with oil are specified in the pertinent instructions.

After the core-coil unit has been impregnated, the oil is drained off, the transformer is opened up, and the core-coil unit is removed from the tank and inspected. Then the transformer is re-assembled.

Heating Up and Drying the Transformers After Inspection

While the transformer is being inspected and re-assembled, the core-coil unit grows damp, therefore, prior to testing the transformer, it is heated up. This is done without vacuum, and the core-coil unit is heated up until the top oil is raised to a temperature of 60 to 70°C. Such a heating-up is frequently called test heating.

Most often, the test heating of completely assembled transformers filled with oil is done by supplying the transformer windings with a direct current which heats up the windings, oil, and the entire core-coil unit. The winding connection diagram and hence, the equivalent resistances of the windings are so chosen as to ensure that the current in any one of the windings does not exceed its rated value. This method is simpler than induction heating since no magnetizing coil need be wound around the tank, and more economical, thanks to a sharp reduction in the power consumed.

Sometimes it happens that during inspection the insulation of the core-coil unit gets some moisture on its surface that cannot be removed by simple heating and distorts the results of the tests on the insulation characteristics. In such cases, resort is made to what is known as test drying.

In test drying, the following operations are carried out.

1. Oil is drained from the tank until its level is 150 to 200 mm below the cover.
2. The tank is evacuated to a pressure of not higher than 15 mm mercury.
3. A direct current is passed through the windings, and the oil is raised to 80°C (if direct current is not available, the transformer is heated up using a magnetizing coil), the oil temperature being monitored by means of two resistance thermometers or thermocouples immersed in the top oil layers.
4. During the entire period of test drying, the oil in the tank is made to circulate constantly with the aid of a pump which draws it out at the top of the tank and pumps it in at the bottom of the tank (the oil is drawn out and pumped in from the opposite sides of the tank).
5. The top oil is held at 80°C and under a vacuum of 5 to 10 mm mercury for the following periods of time: 36 hours for transformers below 80 MV A at 110 to 150 kV, 54 hours for transformers of 80 to 400 MV A at 110 to 150 kV, and 72 hours for transformers larger than 400 MV A at 110 to 150 kV.
6. The heating is stopped, the oil is drained off, and the transformer is cooled down to a temperature of 20 to 25°C (inside the tank) under vacuum, the cooling-down period being not shorter than 20 hours.
7. The tank is filled with oil under vacuum, then oil is added to capacity, so that its level in the conservator is normal, and the transformer is subjected to electrical tests. Should the test results prove to be positive, the transformer is put into operation.

Specific Features of Repairing Individual Components of the Transformers

Terminal Bushings for 110 kV and Over. Where such bushings are to be completely disassembled, they are repaired at specially equipped shops. In medium and major transformer repairs, the necessary work on the bushings involves cleaning and wiping them on the outside, replacing oil, eliminating leaks through faulty seals, drying, and evacuat-

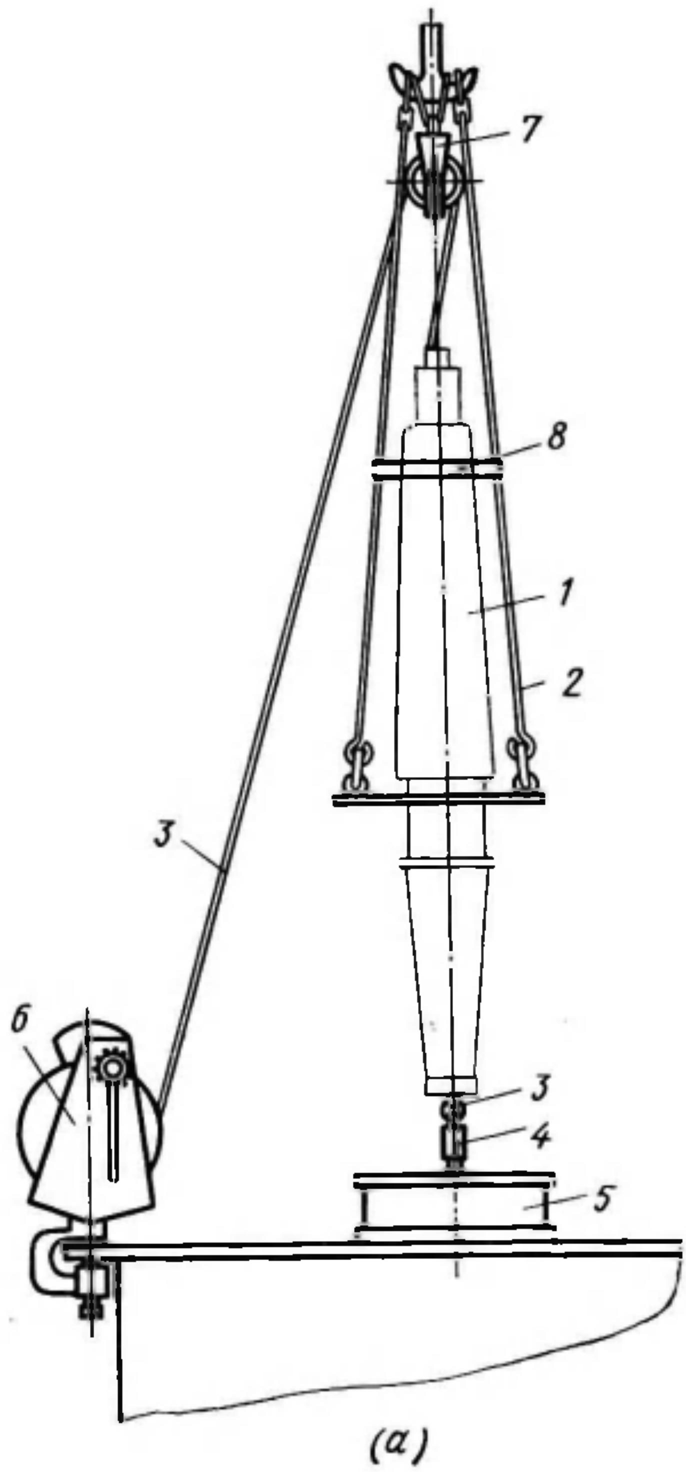
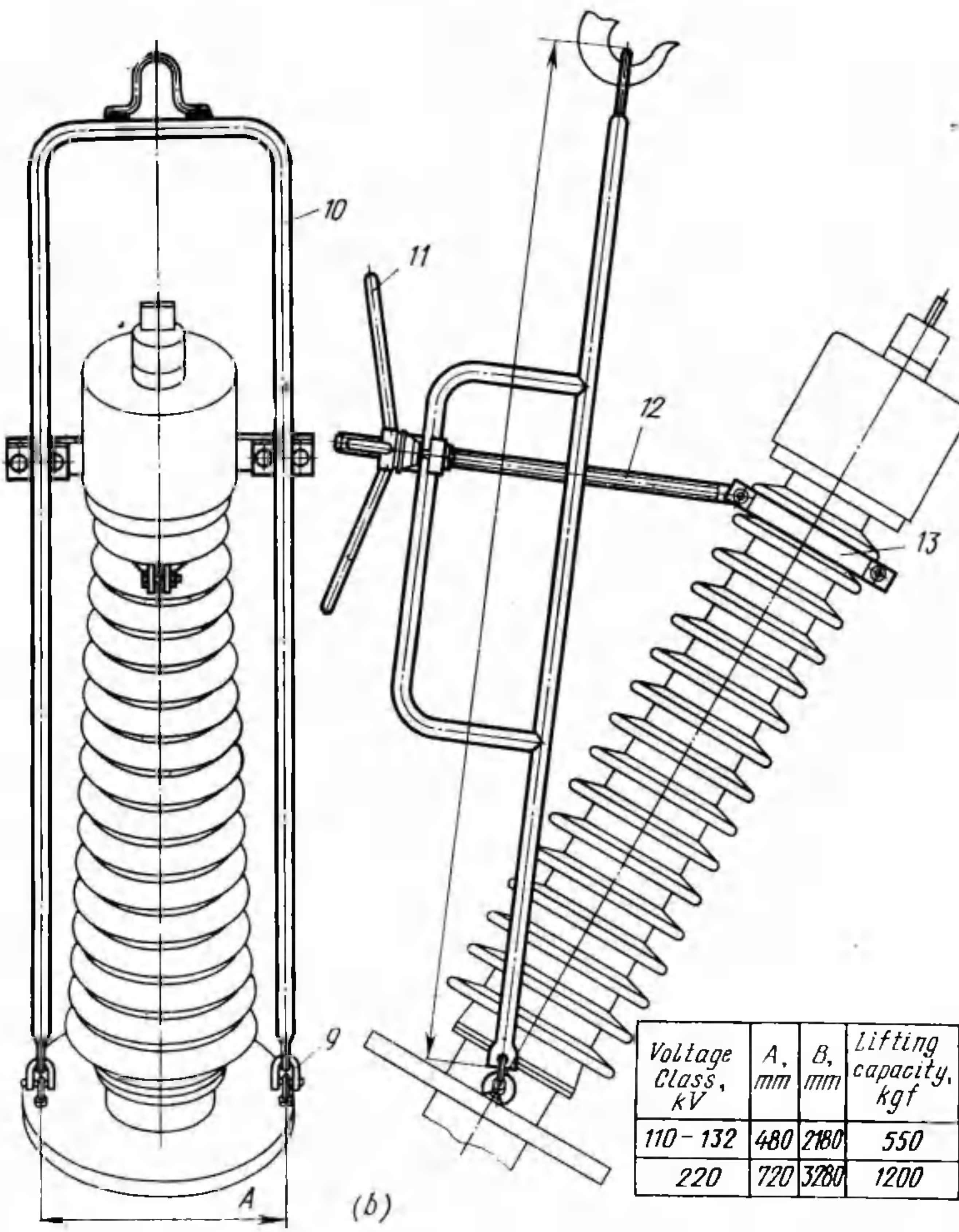


Fig. 6.27. Methods of installing terminal bushings for 110 to 220 kV

(*a*) method of slinging and installing vertical bushings; (*b*) method of installing inclined bushings with the use of a fixture; *1*—bushing; *2*—sling; *3*—steel-wire rope; *4*—lead terminal with a lifting eye; *5*—intermediate flange; *6*—winch; *7*—pulley; *8*—belt; *9*—shackle; *10*—frame; *11*—handwheel for adjusting the bushing inclination angle; *12*—rod; *13*—clamp

ing. When replacing oil in the bushings and drying and evacuating them, one should follow the manufacturer's instructions.

Before mounting them on the transformer, the bushings are tested to see whether their insulation characteristics conform to the standards. The mounting of a bushing on a transformer involves the following two main operations:



Voltage Class, kV	A, mm	B, mm	Lifting capacity, kgf
110 - 132	480	2180	550
220	720	3280	1200

(b)

pulling of the line lead through the bushing and lowering of the bushing on its flange.

Figure 6.27*a* illustrates a method of slinging and installing a vertical bushing *1*. The line lead is pulled through the central tube of the bushing by means of a hand-operated winch *6* whose rope *3* is run around a pulley block *7* and through the bushing tube and then made fast to the lead

terminal *4*. The bushings are lifted and lowered by means of a truck hoist or an overhead travelling crane and sometimes, by means of a hand-operated block and tackle.

The mounting of an inclined terminal bushing is a more difficult and critical operation. Even a slightest imprudence may cause damage to the porcelain shell or, which happens more frequently, to the paper-base laminate tube installed in the intermediate flange (or, sometimes, in the bushing flange itself). Inclined terminal bushings are slinged in the same manner as vertical ones, and the necessary inclination is given to them by means of a hand-operated block and tackle whose fixed pulley block is suspended from the hook of a hoisting mechanism, while the movable one is hooked to a rope or belt strap put around the bushing under its second (from the top) or third watershed (skirt).

A more perfect fixture for installing inclined bushings is shown in Fig. 6.27*b*. With this device, the bushing is fixed more reliably and its inclination angle can easily be adjusted using a rod *12* actuated by a handwheel *11*. The line lead is pulled through the bushing as described above.

Tap-changers. These are carefully inspected before being mounted on the core-coil unit. Worn-out components, as well as burnt contacts and lead insulation, are either replaced or restored. The operation of all the driving gear components is carefully adjusted. All other operations are carried out as in any medium repair.

Cooling System. In medium and major repairs, oil-natural air-blast (System Д) and forced-oil air-blast (System ДЦ) coolers are freed of oil, washed, and tested for leak tightness. Leaky cracks, if there are any, are stopped by electric welding. The pumps and electric motors are disassembled, and their seals and, if necessary, bearings are replaced. The insulation resistance of the fan and pump motors and wiring is measured with a megohmmeter. The fan impellers are checked for vibration and balanced, if necessary. All fastenings are tightened up, the cooling system is filled with oil under vacuum, and then it is checked for leak tightness.

Auxiliary Devices and Fittings. The oil conservator, explosion-vent tube, thermosiphon filters, breathers, and oil seals are disassembled, cleaned, and washed. Then they are tested for leak tightness, and leaks, if any, are

stopped by electric welding. All the inner and outer surfaces are painted. The filters and breathers are filled with fresh or regenerated silica gel. The control and protection instruments and devices are repaired and tested at a laboratory. All sealing gaskets are replaced by new ones.

Review Questions

1. What is the sequence of operations in disassembling the core-coil unit?
2. What methods of removing old insulation from the core plates do you know?
3. List the operations in mounting the windings on the core limbs.
4. What is the sequence of operations in re-blading and re-assembling the top yoke of the transformer core?
5. Describe the methods of soldering, brazing, and welding copper and aluminium conductors.
6. What are the operations involved in preparing the transformer for drying-out?
7. What methods of heating the transformer during drying-out do you know?
8. How are transformers dried out and how is the insulation resistance of the transformer windings measured?
9. What are the safety measures to be taken when disassembling the transformer core?

CHAPTER SEVEN

Drying Out, Purifying, and Degassing the Transformer Oil

The oil with which the transformer is to be filled must meet the pertinent standards. The characteristics of its oil gradually deteriorate with time. Therefore, when repairing transformers, the oil is freed of moisture (it is dried), cleaned from mechanical impurities, and degassed; acid oils are regenerated. For these purposes, use is made of various oil-purifying apparatus, equipment, and adsorbents.

7.1. Cleaning the Oil of Moisture and Mechanical Impurities. Regenerating the Oil

There are two common methods of removing moisture and mechanical impurities from transformer oil. These methods are centrifugal separation and filtering.

Centrifugal Separation

By this method, oil is cleaned from water and mechanical impurities by whirling it at high speed in an apparatus called centrifugal oil separator or purifier. Figure 7.1 is an external view of the Model HCM-3 centrifugal oil purifier. The separator drum is placed in a hermetically sealed casing *1* and consists of a large number of cone-shaped plates or disks provided with openings. The plates are stacked up parallel to one another on a common vertical shaft and are spaced a few tenths of a millimetre apart. The purpose of the plates is to separate the oil into thin layers and thus to intensify purification.

The oil enters the separator through a central inlet opening. There are also three outlets arranged one above another. The top outlet serves to drain off the oil in case of an accid-

ental stoppage of the separator or clogging of the drum, that in the middle, to discharge clean oil, and the bottom one, to drain off the separated water together with impurities. The oil to be purified is pumped into the separator and drawn out of it by two gear pumps *2*. Since moisture is removed from oil most intensively at a temperature of 50 to 55°C, the oil separator is equipped with an electric heater *4*.

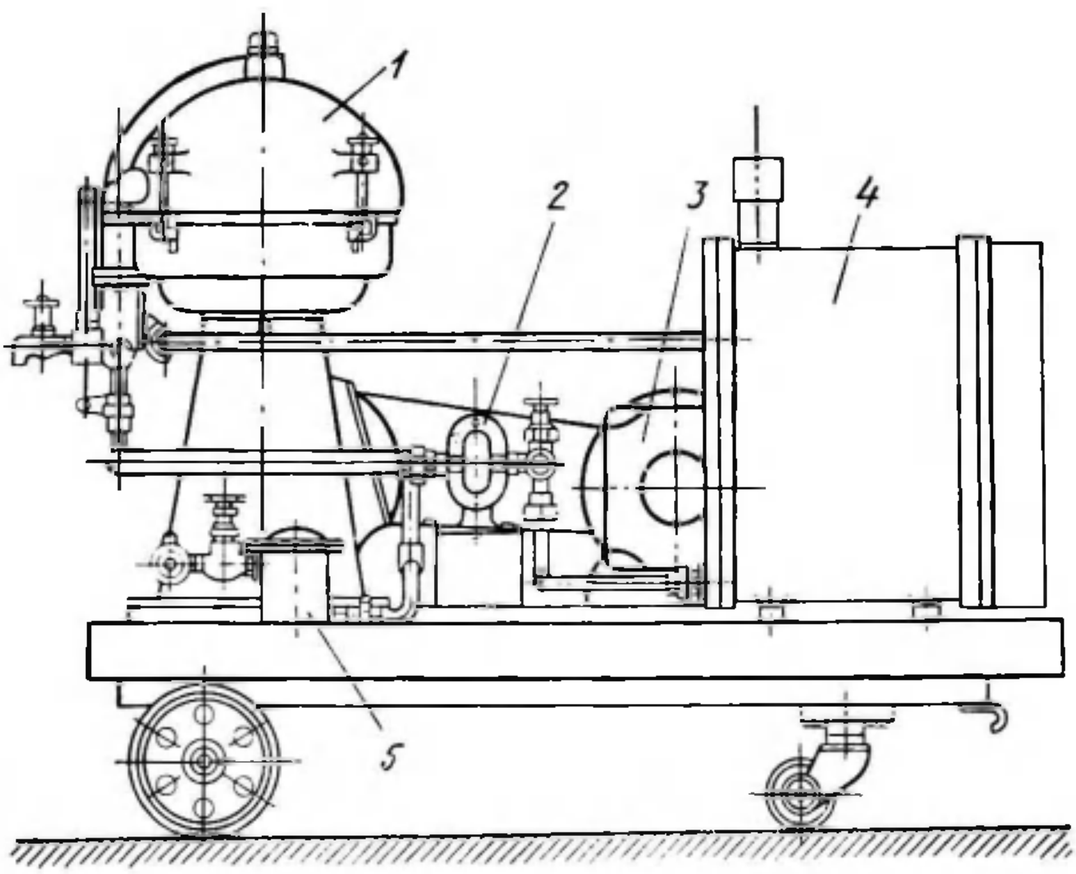


Fig. 7.1. External view of Model HCM-3 centrifugal oil purifier

A filter *5* of fine metal gauze, which is connected into the oil inlet pipe, serves to catch coarse particles and thus prevent their ingress into the apparatus. The separator drum is driven by an electric motor *3* via belt and worm-gear drives. With tbe drum making 6 800 revolutions per minute, the delivery of the separator equals 1 500 litres per hour.

If the oil contains much moisture, the oil purifier is re-adjusted for separating water pre-eminently. This is done by re-arranging the plates of the separator drum. If the moisture content is not very high, the apparatus should be adjusted normally, i.e., to separate both water and mechanical impurities.

To reduce aeration of the oil in the process of centrifugal separation, use is made of vacuum oil separators where oil is cleaned under vacuum.

Filtering

By this method, the oil is cleaned by forcing it through a porous medium with a large number of minute openings

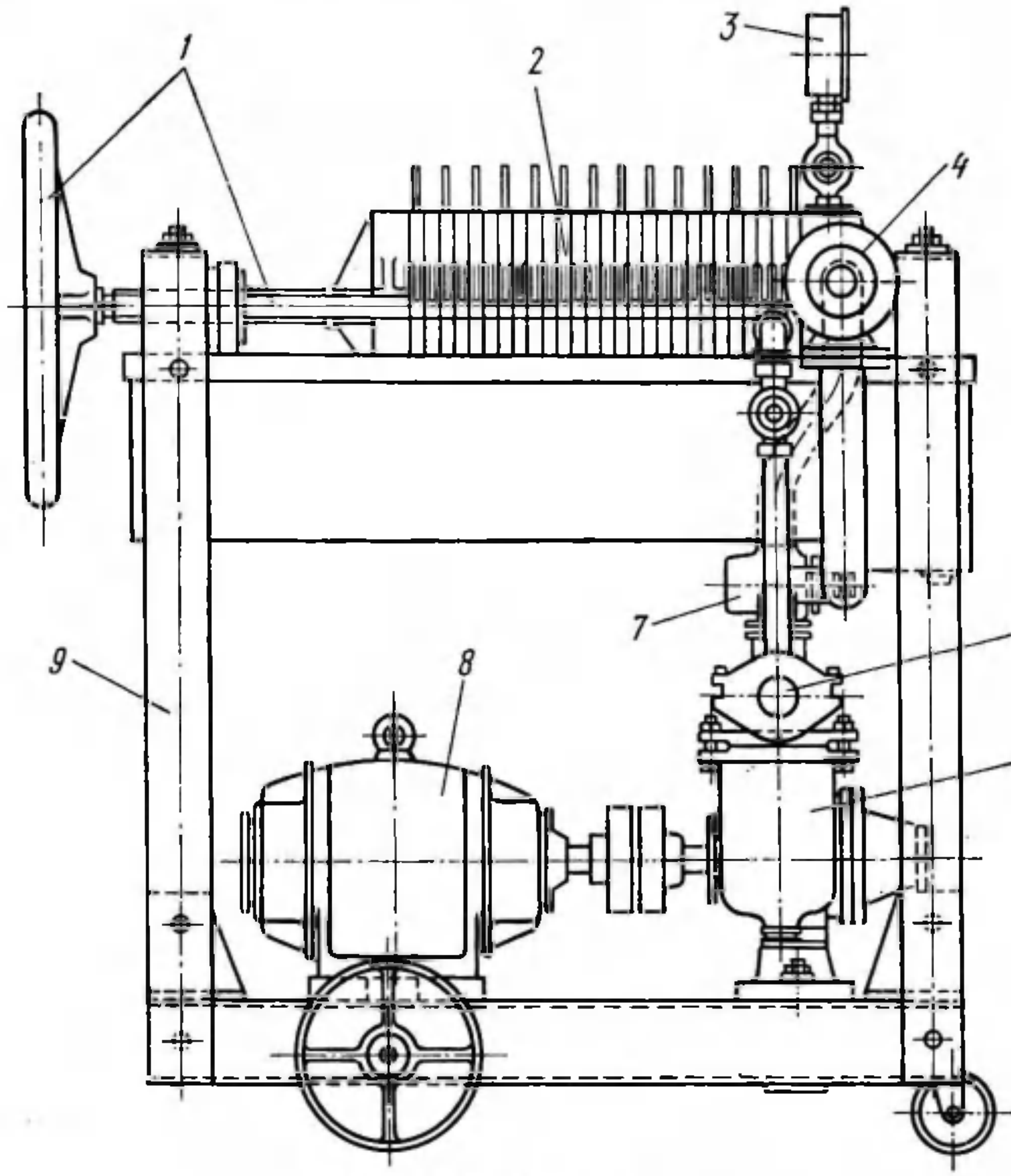


Fig. 7.2. Filter press

1—handwheel and pressure screw; *2*—a set of frames, plates, and filtering material; *3*—pressure gauge; *4*—oil outlet flanged connection; *5*—oil inlet flanged connection; *6*—pump; *7*—coarse oil filter; *8*—electric motor; *9*—bed

in which water and mechanical impurities are entrapped. Such a medium may be a special filter paper, pressboard, or cloth (belting).

An apparatus for filtering the oil is called a filter press (Fig. 7.2). It consists of a set of cast-iron frames (Fig. 7.3*a*) and plates (Fig. 7.3*b*) with filter papers placed between them. The frames and plates are arranged alternately. The

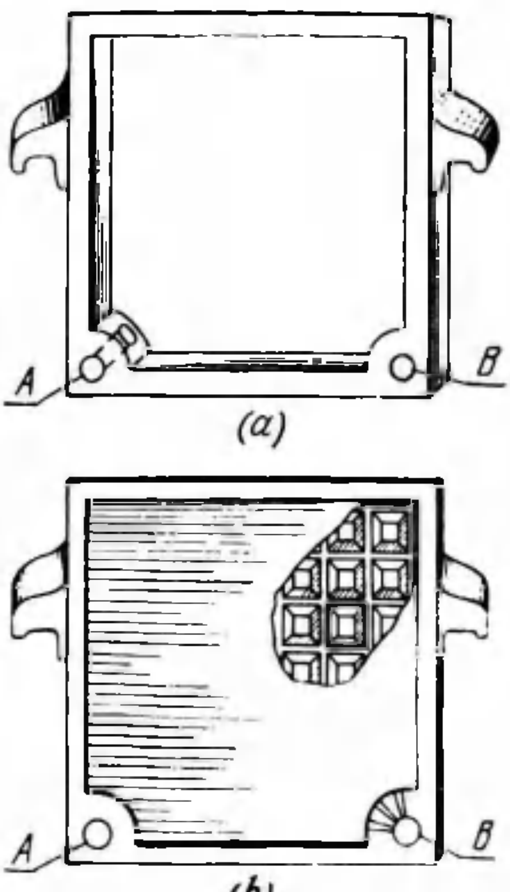


Fig. 7.3. Filter-press components

(*a*) frame; (*b*) plate; *A*—contaminated oil inlet; *B*—purified oil outlet

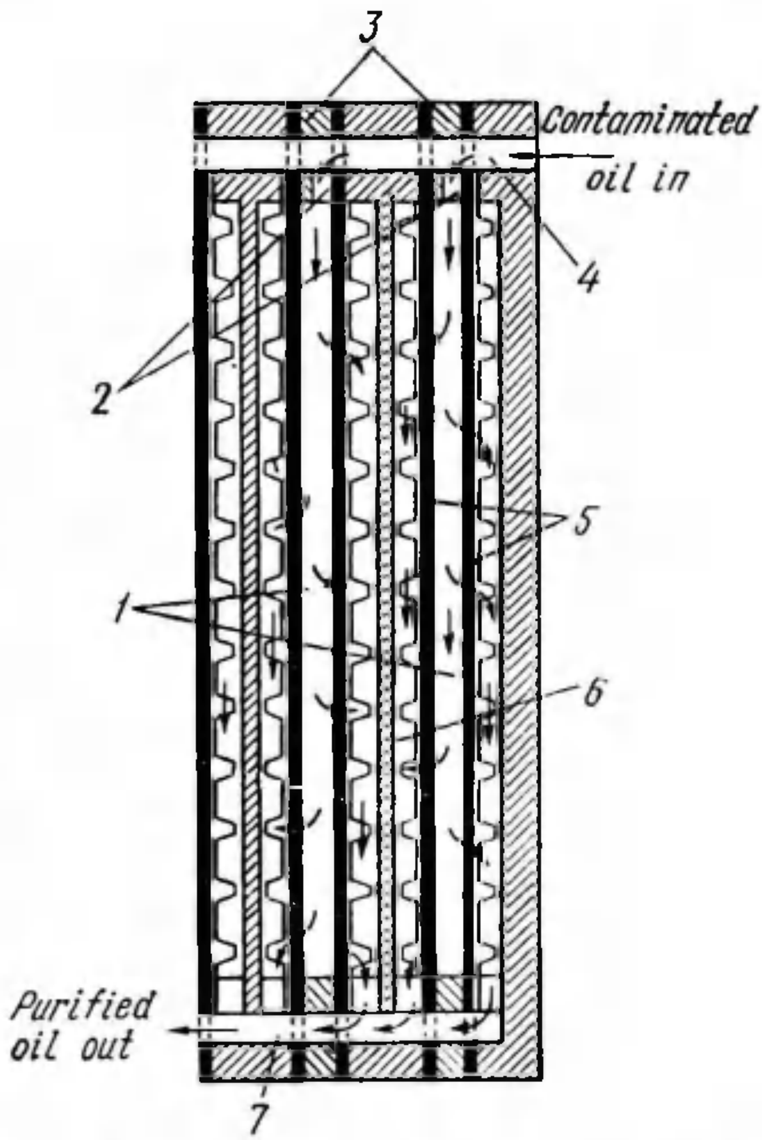


Fig. 7.4. Illustrating the operation of a filter press

whole set together with the filter papers is held securely clamped between two heavy plates by means of a pressure screw.

The frames, plates, and filter papers each has two holes at the lower corners, the hole *A* serving to admit the oil to be cleaned and the hole *B*, to discharge clean oil. Both surfaces of the plates are recessed by longitudinal and transverse V-grooves which do not reach the edges of the plates

and divide their surfaces into a large number of regular truncated pyramids.

When the filter-press elements are stacked up, the holes *A* and *B* in them form common ducts *4* and *7* (Fig. 7.4). The oil to be filtered is pumped into the duct *4* from which it goes through holes *2* drilled at one of the lower corners of the frames *3* into chambers *1* formed within the frames, and then it is forced through the filter papers *5* on the sides of the chambers. Having percolated through the filter papers, the oil, now purified, enters the grooves in the plates *6* and flows by them into the common duct *7* via slots made at one of the lower corners of the plates. From the duct *7* the filtered oil goes to the outlet of the filter press. The parallel connection of the chambers increases the filtering surface and hence, the delivery of the filter press.

The oil to be cleaned is pumped into the filter press under a pressure of $(4 \text{ to } 6) \times 10^5$ Pa. An increase in the oil pressure during operation of the filter press indicates that the filter papers have got cloged and must be replaced. The incoming oil is first coarsely cleaned in a special gauze filter connected into the inlet pipe. On the outlet pipe there is a cock for sampling the purified oil.

Drying the Oil in Zeolite Dehydrator Plants

Zeolite dehydrator plants are widely used for drying the transformer oil. In these plants, dehydration is effected by single-stage filtering of the oil through a layer of molecular sieves—man-made zeolites of the NaAl type. Usually a zeolite plant (Fig. 7.5) consists of three to four adsorption columns (or simply adsorbers) *6* operating in parallel and containing 50 kg of zeolite each. An adsorber is a hollow metal cylinder filled up with zeolite. For good contacting, it is essential that the size of the adsorber be such as to ensure that the ratio of the height of the granulated zeolite column in the cylinder to the inner cylinder diameter is not less than 4 : 1. At the bottom of the adsorber there is a metal gauze which supports the molecular sieves. The top neck of the adsorber is covered with a detachable metal gauze. The oil is forced through the adsorber by means of a pump.

To heat the oil, the plant is equipped with a heater *3*—a metal tank with connections for the oil lines, pressure gauge *4*, temperature indicator, and cartridge-type electric heaters (usually Type ТЭН-12).

There are also two filters *5*, one of them being installed at the inlet to the plant (to clean the oil from mechanical impurities) and the other, at the outlet from it (to stop zeol-

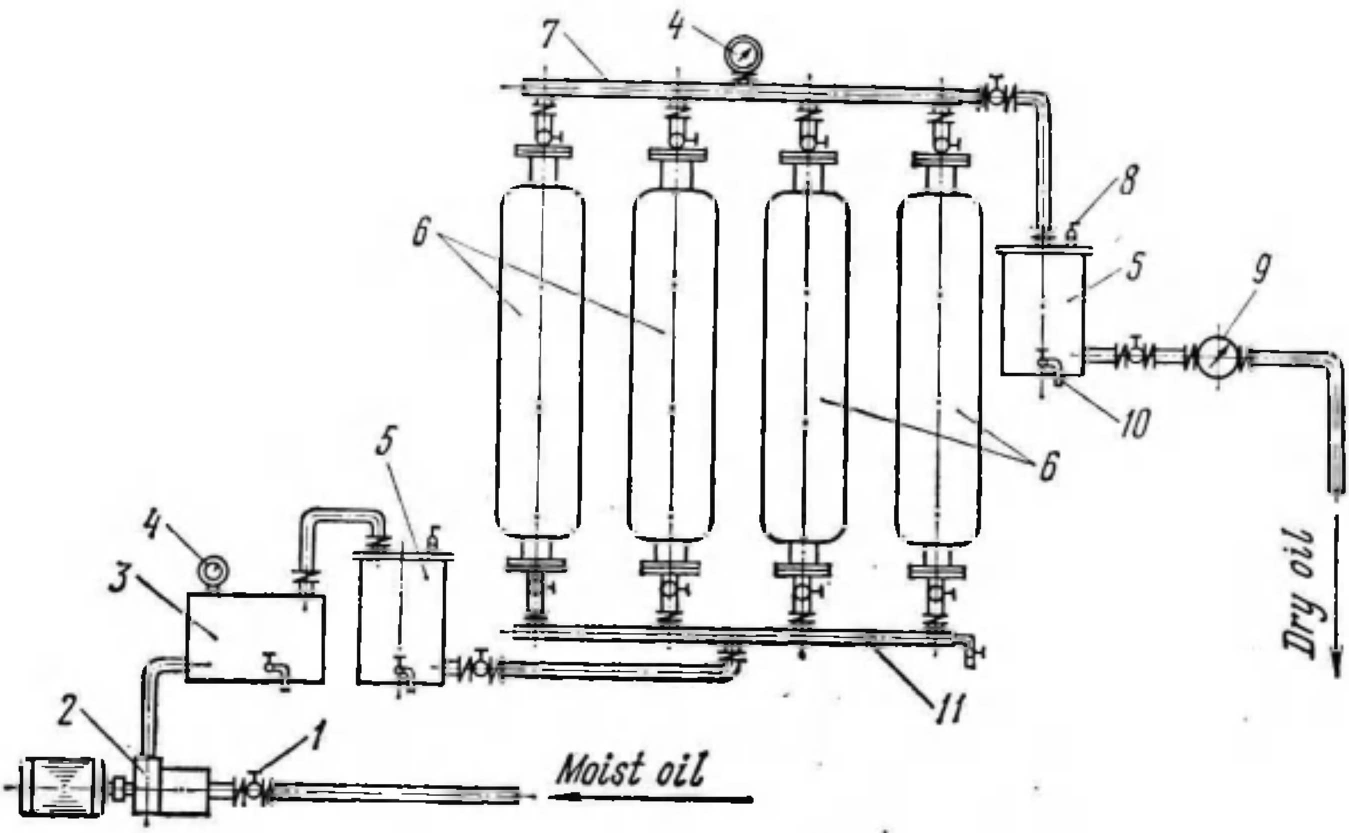


Fig. 7.5. Zeolite plant for drying oil

1—valve; *2*—pump; *3*—electric oil heater; *4*—pressure gauges; *5*—filters; *6*—adsorption columns; *7*—top header; *8*—air-bleed valve; *9*—flow meter; *10*—oil drain and sampler valve; *11*—bottom header

ite granules and crumbs in case of damage to the gauze covering the top necks of the adsorbers).

The amount of zeolite necessary to dry a given batch of oil ranges from 0.1 to 0.15% of the mass of oil. In one filtering cycle, the breakdown voltage of the transformer oil can be increased from 10-12 to 58-60 kV. The oil is dried at a temperature of 20 to 30°C and a flow rate of 1.1 to 1.3 t/h. Practically, 50 t of oil will take about 48 hours to dry in a plant charged with 100 kg of zeolite. In zeolite dehydration, the acid number and alkali test of the oil remain unchanged.

Zeolites eagerly pick up moisture from air, therefore, zeolite-filled adsorbers must always remain filled with oil, and fresh zeolites must be stored in moisture-tight containers. The adsorptive properties of zeolites can be repeatedly reclaimed by blowing air at a temperature of 300 to 400°C through the adsorbers for 4 to 5 hours.

Regeneration of Acid Oils

There are a number of chemical methods for deep regeneration of oils, the chief amongst them being the acid-alkali-clay method. By this method, oil is first treated with sulphuric acid that binds all unstable oil compounds into acid tar. The tar is removed through settling, and the rest of sulphuric and organic acids is neutralized by treating the oil with alkali. Then the oil is washed with distilled water, dried, and treated with bleaching clay to ensure complete neutralization. After final filtering, fully reclaimed oil is obtained.

Such porous substances as bleaching clay, alumina, and silica gel have a very large surface area and possess the ability to pick up some components from a solution and concentrate them on the surface. This phenomenon is known as *adsorption*.

In transformer repair practice, silica gel is used for shallow regeneration of the transformer oil through adsorption. Silica gel is advantageous in that it can be used over and over again. To reclaim silica gel for the repeated usage, it is calcined at a temperature of 300 to 500°C.

When repairing transformers in situ, silica gel is usually used for reclaiming slightly oxidized oils which do not require deep chemical regeneration. In this case, the oil is repeatedly forced through an adsorber—a small tank filled with calcined silica gel. As a rule, the oil is made to circulate through the adsorber by means of the pump of a centrifugal oil separator or filter press, which is connected into the outlet pipe of the adsorber. As with the other methods of purification, the oil is heated up while being reclaimed.

7.2. Degassing the Transformer Oil

The presence of atmospheric oxygen in the transformer oil causes its oxidation and deterioration of its dielectric properties, because of the ionization and breakdown of the gas inclusions under the effect of strong magnetic field. Under atmospheric pressure, the oil usually contains about 10% air (by volume), the proportion of the gases constituting the air dissolved in the transformer oil differing from that of the gases in the atmospheric air. It is common knowledge that air contains 78% nitrogen and 21% oxygen. But the air dissolved in the transformer oil contains 69.8% nitrogen and 30.2% oxygen. Also, the solubility of air in the oil increases with temperature.

When repairing or installing transformers, the oil is degassed under vacuum in order to prevent its deterioration and premature ageing. Prior to degassing, the oil is dried to not more than 0.001% moisture (10 g of water per cubic metre of oil).

The oil is degassed in special apparatus called vacuum degassers. As a rule, a degasser consists of two metal tanks filled with Raschig rings that increase the surface for the oil to spread over. On the cover of each tank there is a sprayer whose purpose is to uniformly distribute the oil over the entire volume of the tank. The tanks are evacuated by means of vacuum pumps (usually Type BH-6). While flowing in thin layers down the surfaces of the rings, the oil is degassed to 0.04% gas (by volume). From the degasser the oil goes into the transformer tank, the tank being evacuated to the same pressure as the degasser. The air content of the oil is determined by means of a special apparatus at a laboratory.

The transformer is filled with the degassed oil until the oil level is within 150 to 200 mm of the tank cover. The free space above the oil is filled with dry nitrogen. As nitrogen dissolves in the oil, make-up gas is admitted into the tank until the oil is completely saturated with nitrogen.

Both stationary and portable degassing plants are used in transformer repair practice.

When changing over to nitrogen or film protection, the oil must be dried and degassed under vacuum as described above.

Review Questions

1. Tell about the methods of cleaning the transformer oil from mechanical impurities and moisture.
2. Describe the operating principles of the centrifugal oil purifier and filter press.
3. Tell about the zeolite treatment of the transformer oil and describe the properties of zeolites.
4. What are the reasons for the nitrogen and film protection of transformers?
5. What is the purpose of degassing the transformer oil?

CHAPTER EIGHT

Transformer Testing

During repair, individual units of the transformer and then the finally assembled transformer itself are subjected to various tests to make sure that there are no defects or departures from specifications. The results of all tests and measurements are entered in a special document called the "Test Sheet".

All transformer tests may be classed as preliminary, intermediate, and final (check).

Preliminary tests are made where the transformer has been put out of service for planned repair (inspection) or has failed. The tests are carried out prior to opening up the transformer and are intended to find out the nature of the fault, if any, and see if drying of the transformer would be required.

The preliminary tests include:

(1) transformer oil test;

(2) measuring the insulation resistance of the windings;

(3) measuring the D.C. resistance of the windings;

(4) determining insulation characteristics.

Intermediate tests are made in the course of repair, when the transformer is disassembled. In this case, the scope of tests and measurements depends on the scope of the repair work. Where the core-coil unit has not been disassembled, but has underwent only minor repair, the intermediate tests include:

(1) measuring the insulation resistance of the core clamping studs and yoke clamps;

(2) testing the insulation resistance of the clamping studs by applied voltage;

(3) testing the terminal bushings by applied voltage.

Where the core-coil unit has been disassembled, the scope of the intermediate tests is substantially increased.

Final (*check*) *tests* are made on the repaired and reassembled transformer. These include:

(1) transformer oil test;
(2) measuring the insulation resistance;
(3) determining the transformation ratio (the ratio test);
(4) determining the phase-displacement group of the winding connection;
(5) determining the insulation characteristics;
(6) testing the major insulation by applied voltage;
(7) measuring the copper loss and the short-circuit (impedance) voltage (the short-circuit test);
(8) testing the interturn insulation by induced voltage;
(9) measuring the no-load losses and exciting current (the no-load test);
(10) measuring the D.C. resistance of the windings.

If the transformer has been opened up for inspection, but its core-coil unit has not been disassembled, it is subjected to check tests listed under items (1), (2), (5), (6), and (10) only.

It is recommended that tests and measurements should be carried out in the order they occur in the above list. For instance, it is not at all immaterial which of the two—the transformer insulation or oil—is tested first, because an insulation breakdown in the applied voltage test may result from the poor quality of the oil. The interturn insulation should be tested after testing the major insulation, otherwise a puncture of the interturn insulation that might occur during the major insulation test will not be detected. Also, it is impermissible to measure the D.C. resistance of the windings prior to the short-circuit test, because during this test some leads may char or even burn out altogether as a result of poor soldering of their connections or bad condition of the tap-changer contacts, and it is exactly such defects that the measurement of the D.C. resistance of the windings is intended to reveal.

8.1. Testing the Transformer Oil

The transformer oil is subjected to the dielectric strength (breakdown) test, dielectric loss test, and chemical analysis.

Testing for Dielectric Breakdown. The oil is tested in a

special oil-testing apparatus (Fig. 8.1). The oil sample should be taken from the oil-sampling valve or from one of the valves at the bottom of the transformer tank, the sample container being a dry glass vessel with a capacity of not less than 0.5 l. Then the standard oil-testing spark gap (Fig. 8.1*a*) of the apparatus is filled with the oil. The spark gap comprises a special porcelain receptacle *1* and two

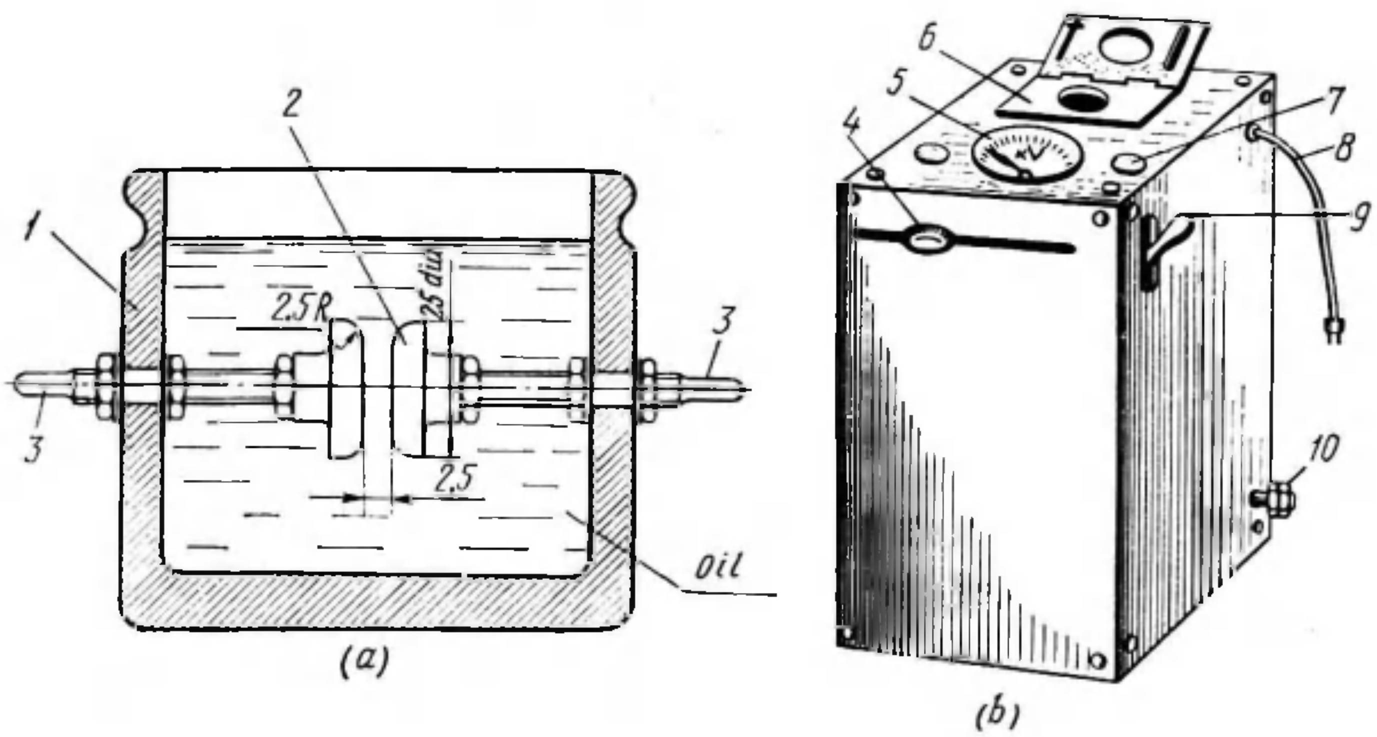


Fig. 8.1. Oil-testing apparatus

(*a*) standard oil-testing spark-gap; (*b*) external view of the apparatus; *1*—porcelain vessel; *2*—flat electrode; *3*—conductor; *4*—regulating transformer control handle, *5*—kilovoltmeter; *6*—spark-gap socket with a cover; *7*—control lamp; *8*—mains cable; *9*—circuit breaker handle; *10*—earthing terminal

flat electrodes mounted on current-carrying rods *3* of brass, across which a high voltage is applied from a step-up regulating transformer built in the apparatus.

After filling the receptacle, one should allow 20 min for air bubbles to escape from the oil before applying voltage. Then the apparatus is connected to A.C. mains by means of a cable *8* (Fig. 8.1*b*) with a plug, and its switch *9* is thrown in. The voltage across the spark gap is raised up to breakdown by smoothly shifting a knob *4*, the breakdown value being measured by means of a kilovoltmeter *5*.

Six breakdowns should be made at 10-minute intervals. The first result is not taken into account, and the average of the subsequent five is taken as the breakdown voltage of

the oil. This voltage must comply with the standard values set depending on the kind of oil and the voltage rating of the transformer (see Table 8.1).

Table 8.1

Standard Breakdown Voltage Values (in kV) for Transformer Oil

Kind of oil	Transformer voltage rating, kV			
	up to 15 inclusive	from 15 to 35 inclusive	from 60 to 220 inclusive	330 and over
Fresh, dry oil	25	30	40	50
Oil in transformer in service	20	25	35	45

For outdoor transformers, it is desirable, where possible, to sample the oil in dry weather in summer and in frosty weather in winter. In the winter time, the sample container brought indoors must be kept closed until the oil in it reaches the room temperature, otherwise water vapours will condense inside the container, thus deteriorating the dielectric strength of the oil. The oil sample should be taken very carefully, so that neither mechanical impurities nor moisture can get in the oil. Before taking the sample, one should drain two or three litres of oil from the transformer and wash the sample container with it several times. The filled container should be tightly closed with a ground-in stopper and only then dispatched for testing.

Testing for Dielectric Loss. The test consists in determining the loss tangent. For the oil in a transformer in service, the loss tangent must not exceed 1% at a temperature of 20°C and 7% at 70°C. For fresh, dry oil, it must range from 0.2 to 0.4% (depending on the grade of oil) at a temperature of 20°C and from 1.5 to 2.5% at 70°C.

Chemical Analysis. This is intended to see whether the chemical characteristics of the transformer oil comply with the standard specifications. The analysis is essential, because any changes in the chemical characteristics of the oil bear witness to the technical condition of the transformer. For example, an increase in the acid number of the oil, or a decre-

ase in its flash point, indicates that the oil has decomposed as a result of local overheating in the transformer.

Chemical analysis may be thorough or brief. In transformer repair practice, the oil is usually subjected to a brief chemical analysis which includes the determination of the acid number, flash point, water extract reaction, content of suspended carbon and mechanical impurities, and transparency. The pertinent standards stipulate that no mechanical impurities and water-soluble acids and alkalies be present in the transformer oil.

The acid number indicates how many milligrams of potassium hydroxide (KOH) are required to neutralize the acids contained in one gram of oil. For fresh, dry oil, the acid number must not exceed 0.05 and for used oil, 0.25. The flash point of the transformer oil, when fresh, must not be lower than 135°C and it is allowed to drop in service by not more than 5 deg C. Where a thorough chemical analysis is performed, the oil is additionally tested for viscosity, stability, density, congealing point, etc.

The oil for transformers using nitrogen or film protection is tested for moisture and gas content. The moisture content (by volume) must not exceed 0.001% and the gas content, 0.1%.

8.2. Measuring the Insulation Resistance

Insulation resistance measurements enable one not only to evaluate the quality of the transformer insulation, mainly the degree of dryness, but also to reveal gross defects so that damage to the insulation in subsequent high-voltage tests can be avoided. Insulation resistance is measured by means of megohmmeters. A megohmmeter consists of a power source and a measuring system. The power source is a hand-operated or electrically-driven D.C. generator built in the instrument.

Figure 8.2 shows a schematic diagram of a 500-V megohmmeter and the external view of a 2 500-V megohmmeter. If the instrument terminals marked L (line) and E (earth) are connected to points a and b between which the insulation resistance R_{ins} is to be measured, and the crank *3* of the megohmmeter is rotated, currents will flow through this

resistance and through coils *1* and *2* which are mounted for rotation on a common axle and placed in the field of a permanent magnet. The interaction of the currents in the coils with the field of the magnet produces a torque causing

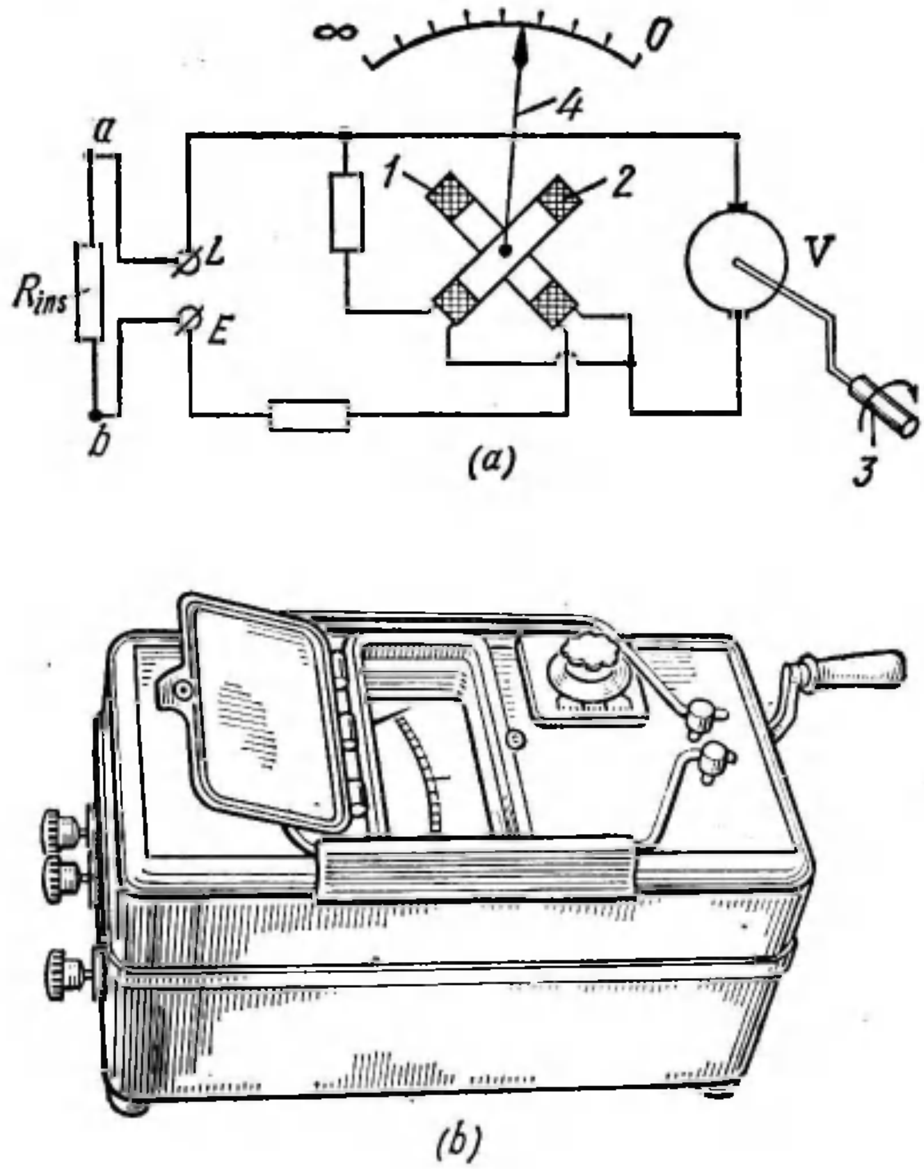


Fig. 8.2. Megohmmeter

(*a*) schematic diagram of a 500-V megohmmeter; (*b*) external view of a 2 500-V megohmmeter

the coils to deflect. The deflection angle of a pointer *4* rigidly coupled to the movement of the instrument depends on the relation between the currents in the coils. The scale of the instrument is graduated to read insulation resistances in the 0-10 000 MΩ range.

In this country, megohmmeters are available in voltages of 500, 1 000, and 2 500 V. In transformer repair practice, the 1 000-V megohmmeters are used for measuring insulation resistance in oil-immersed transformers of up to 63 kV A

and in all dry-type transformers of up to 1 kV, and the 2 500-V instruments are employed for larger transformers operating at voltages of 10, 35, 110, 220 kV and upwards.

The insulation resistance of a transformer is measured between the windings collectively (i.e., with all the windings being connected together) and the earthed tank (earth), and between each winding and the tank, the rest of the windings being earthed. Thus, for a two-winding transformer the following three measurements are to be taken:

between the HV winding and tank, the LV winding being earthed;

between the LV winding and tank, the HV winding being earthed;

between the HV and LV windings collectively and the tank.

This measurement procedure may be written in brief as follows: HV—tank, LV; LV—tank, HV; HV + LV—tank.

For a three-winding transformer five measurements are necessary:

between the HV winding and tank, the MV and LV windings being earthed;

between the MV winding and tank, the HV and LV windings being earthed;

between the LV winding and tank, the HV and MV windings being earthed;

between the HV and MV windings collectively and the tank, the LV winding being earthed;

between the HV, MV, and LV windings collectively and the tank.

In this case, the measurement procedure is written as follows: HV—tank, MV, LV; MV—tank, HV, LV; LV—tank, HV, MV; HV + MV—tank, LV; HV + MV + LV—tank.

When measuring the insulation resistance of a current-carrying component part relative to earth, the following procedure can be employed. Two flexible, well-insulated conductors should be connected to the line and earth terminals of a megohmmeter. The free ends of the conductors must have metal terminals (probes) with insulated handles. The probe marked "Earth" should be touched to the transformer tank (that must be earthed) and the other probe, to a current-carrying bar or lead connected to the winding

under test, and the megohmmeter should be cranked at a speed indicated in its certificate (usually 120 rpm). 60 seconds after the start of the cranking the insulation resistance should be read on the megohmmeter scale. The value thus obtained is called 60-second insulation resistance and is designated $R_{60''}$.

When measuring the insulation resistance between different windings, the megohmmeter probes should be connected directly to the windings. If there is a spark-gap protector on the transformer, it should be disconnected, otherwise it will break and thus distort the measurement results.

The resistance of insulation depends on its temperature, therefore, when testing insulation, the temperature should also be measured. In oil-immersed transformers, the temperature of the top oil is conventionally taken as the insulation temperature, while in dry-type transformers, it is the ambient temperature that is taken as the insulation temperature.

The results of the insulation resistance measurements should be checked against the manufacturer's specifications or against the results of the previous tests. If there are no such data, the check should be made against the values specified in the pertinent standards. For new oil-immersed transformers of Soviet make, the 60-second insulation resistance as a function of the winding temperature and voltage class is given in Table 8.2. The values of $R_{60''}$ given in the

Table 8.2

Minimum Permissible Insulation Resistance $R_{60''}$ (in MΩ) for Oil-Immersed Transformer Windings

Transformer voltage class, kV	Winding temperature, °C						
	10	20	30	40	50	60	70
Up to 35	450	300	200	130	90	60	40
110	900	600	400	260	180	120	80

table refer to all the windings of a given transformer. They also apply to transformers that have underwent overhauling with the replacement of the windings and insulation.

The magnitude of the insulation resistance is not always indicative of the degree of dryness of the transformer, there-

fore, use is made of an additional characteristic, known as absorption coefficient (designated K_{abs}) which is the ratio of the 60-second insulation resistance to the 15-second insulation resistance, i.e., $K_{abs} = R_{60''}/R_{15''}$.

For power transformers with dry insulation, the absorption coefficient at a temperature of 10 to 30°C must not be lower than 1.3.

Before measuring the insulation resistance of an assembled transformer, its terminal bushings must be carefully wiped with a piece of dry cloth. When handling a megohmmeter, one should observe accident prevention rules. Transformer windings possess a substantial capacitance, therefore, the current-carrying parts can only be touched after electric charge has been removed from them. For this purpose, these parts should be connected to the earthed tank. When doing this, one should wear rubber gloves. It is absolutely prohibited to use a megohmmeter to test a transformer under voltage.

8.3. Testing the Insulation

Applied Voltage Test

This test is made to check the dielectric strength of the insulation between the windings operating at different voltages (HV, MV, LV) and between each of these windings and the earthed parts of the transformer. This test is frequently called the *major-insulation test* of the transformer.

The winding to be tested is short-circuited and connected to the high-voltage terminal of a suitable step-up testing transformer with the return circuit connected to the earthed tank of the transformer under test. The terminals of all the other windings are connected together and earthed to the tank. The voltage should be raised gradually and without interruption from zero to the test value.

Figure 8.3 shows a schematic diagram of testing the HV winding of a three-phase transformer *5* by applied voltage. As seen from the figure, the terminals A, B, and C of this winding are connected together and to the high-voltage terminal of a testing transformer *4*. The terminals a, b, and c

of the LV winding are all connected to the earthed transformer tank by means of a common wire.

Using a regulating transformer *1* connected to a 50-Hz A.C. power source, the voltage of the transformer *4* is smoothly raised to the test value. If during 1 minute from the moment the test voltage is applied an ammeter *3* does not show any increase in the supply current and a voltmeter *2* does not

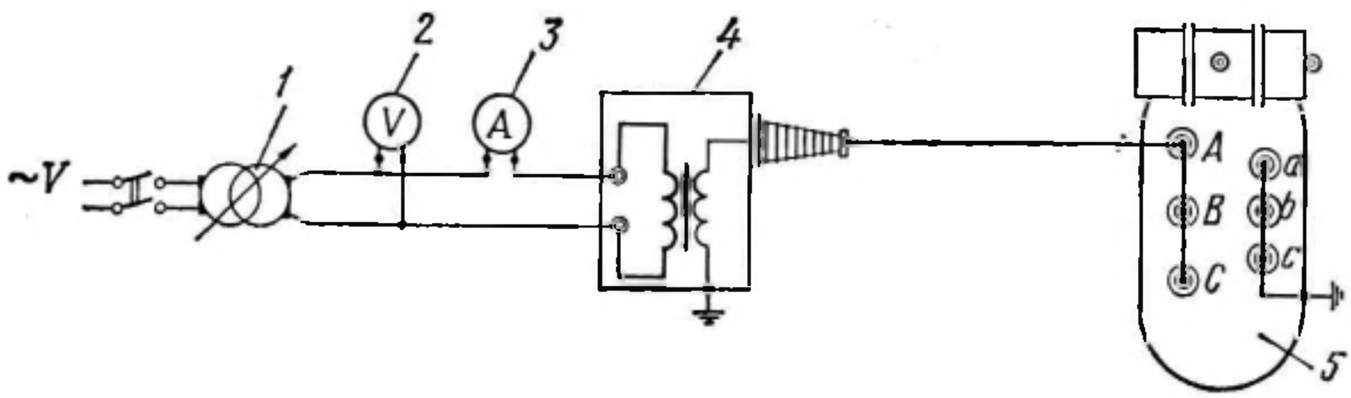


Fig. 8.3. Schematic diagram of testing a HV winding by applied voltage

read any decrease in the supply voltage, and no discharges (crackles) are heard inside the transformer, the voltage is gradually brought down to zero and the transformer is considered to have stood the test. All other windings are tested in the same way.

The HV winding is usually the first to be tested, then comes the MV winding and after that, the LV one. Breakdowns and partial discharges are accompanied by sound phenomena and jump-like changes in the instrument readings. A ringing

Table 8.3

Test Voltage Values (in kV) for Major-Insulation Tests of Transformers

Transformer type	Transformer voltage rating, kV						
	up to 0.69	3	6	10	15	35	110
Oil-immersed	5	18	25	35	45	85	200
Dry	3	10	16	23	37	—	—

sound indicates that an oil gap has broken. A breakdown of solid insulation is, as a rule, accompanied by a dull sound.

After filling the tank, one should allow 12 hours for air bubbles to escape from the oil before applying test voltage.

The test voltage depends on the voltage rating and type of the transformer (see Table 8.3).

When testing transformers after medium repair (inspection), the test voltage values listed in the table should be reduced by 10%.

Induced Voltage Test

The dielectric strength of the interturn, interlayer, interdisk, and interphase insulation is tested by induced voltage (Fig. 8.4). In this test, one of the windings (usually the LV one) is energized, while the others are left open-circuited.

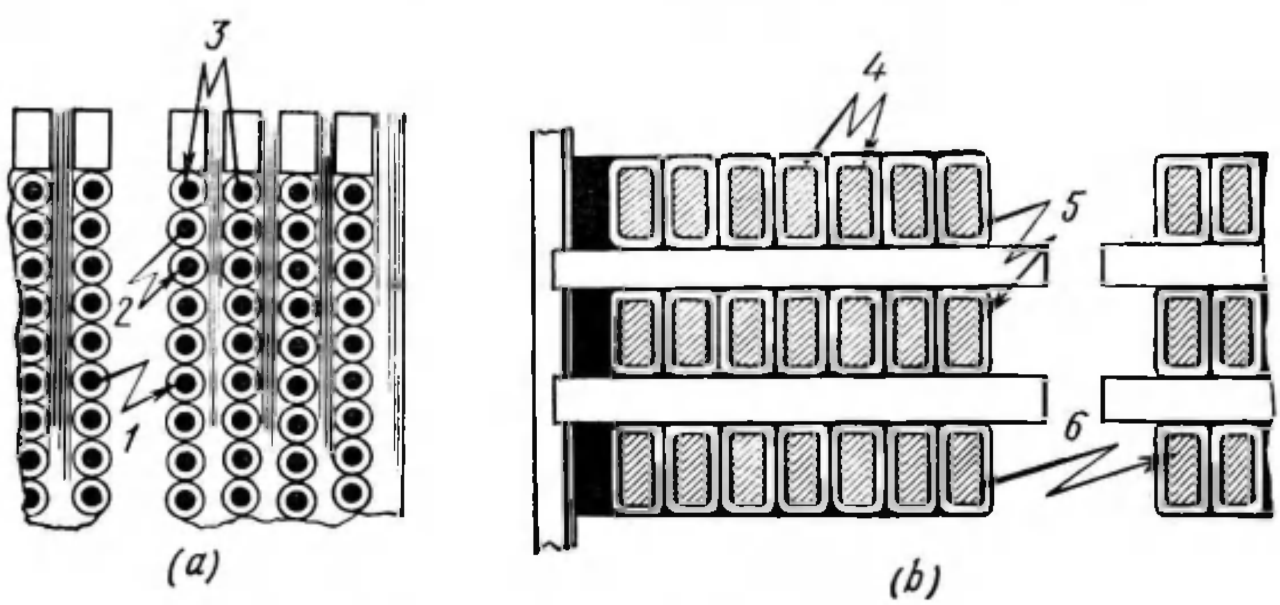


Fig. 8.4. Testing insulation by induced voltage

(*a*) cylindrical winding; (*b*) continuous-disk winding; *1* and *6*—interphase insulation; *2* and *4*—interturn insulation; *3*—interlayer insulation; *5*—interdisk insulation

Figure 8.5 shows a schematic diagram of testing a three-phase transformer *2* by induced voltage. The currents and voltages on the supply side are monitored by means of ammeters and a switch-selectable voltmeter 3. The test voltage is supplied from a generator *1*. Using the generator field control, the test voltage is gradually raised from zero to the test value. The test is run for a period of 1 min and then the test voltage is smoothly brought down to zero.

When the supply frequency is 50 Hz, the test voltage is taken at 130% of the rated voltage for transformers clamped without the use of through clamping studs and at 115% for those clamped with studs. If in the course of the test there are no jump-like changes in the phase currents, the

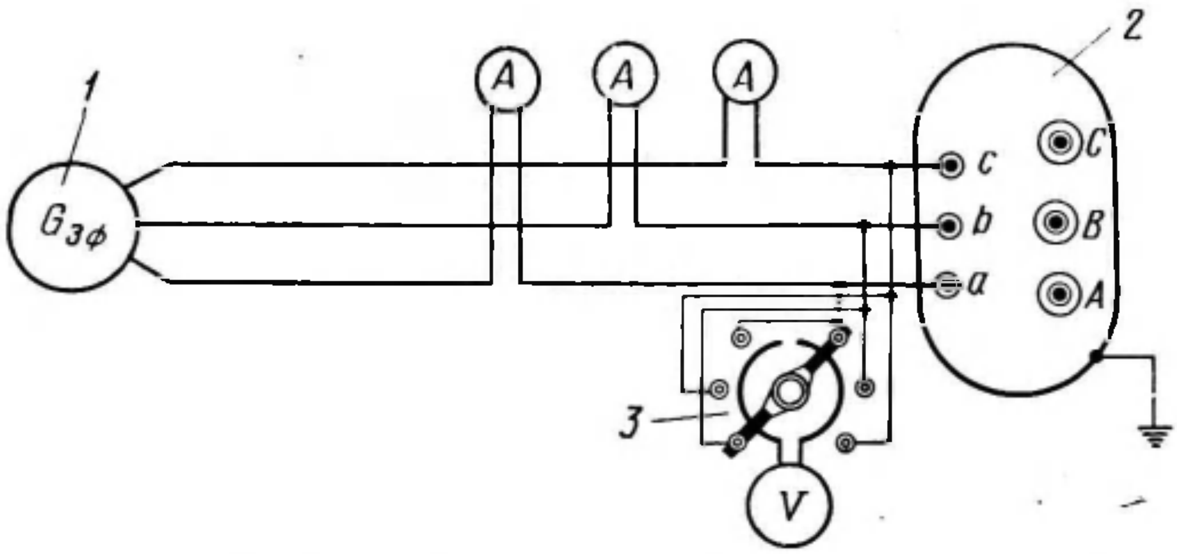


Fig. 8.5. Schematic diagram of testing a transformer by induced voltage

phase voltages are symmetrical, smoke and gas do not escape from the transformer, and no crackles are heard inside it, the transformer is considered to have stood the test.

8.4. Determining the Transformation Ratio, Phase-Displacement Group of the Winding Connection, and D.C. Resistance of the Windings

The ratio tests are made in order to reveal such defects as may occur when manufacturing and connecting the transformer windings, e.g., wrong number of turns in the regulating and main windings, wrong connection of the windings, and wrong connection of the voltage-control taps to the tap-changer. In these tests, the transformer is energized on one of its sides (usually the HV side) while its other side remains open-circuited (Fig. 8.6).

If the transformer under test is of the three-phase type, all the three phases are energized simultaneously. The applied voltage must be at least 2% of the rated voltage. The voltages on the HV and LV sides are measured simultaneously by means of switch-selectable voltmeters and the

transformation ratio is determined by calculations. It is determined for all phases and voltage-control steps.

The permissible deviation from the design value of the transformation ratio amounts to $\pm 1\%$ for transformers with a ratio of up to 3 inclusive and $\pm 0.5\%$ for all other transformers. The deviations between individual phases must be within 1 to 2%.

From among the existing methods for determining the phase-displacement group of the winding connection, the

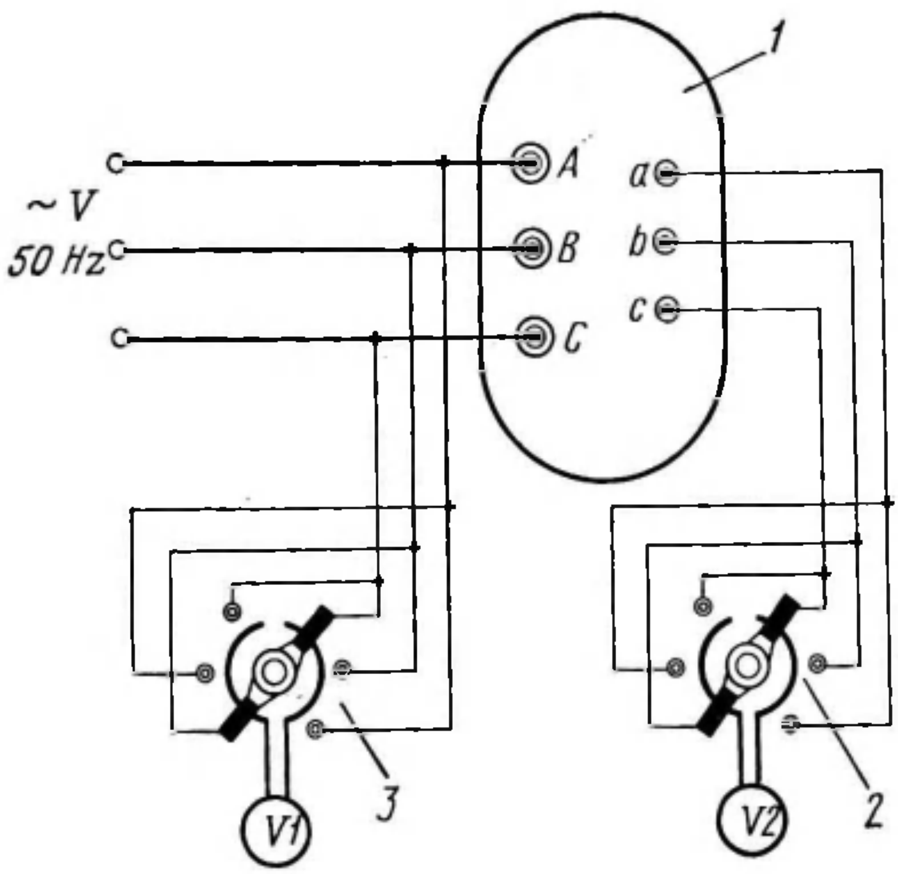


Fig. 8.6. Diagram for measuring the transformation ratio

1—transformer under test; 2—switch-selectable LV voltmeter; 3—switch-selectable HV voltmeter

so-called method of two voltmeters has found the widest application. By this method, the terminals A and a of the HV and LV windings are connected together by means of a metal jumper, and the transformer is excited on the LV side with a low voltage. The phase-displacement group is then determined by measuring the voltages between the various remaining terminals and comparing them with the vector diagrams or tabulated data supplied by the manufacturer.

Poor-quality soldering, bad contacts between the leads and tap-changer, breaks in the parallel conductors of the windings, and other defects that may occur in the course of repair cause an increase in the winding resistance. Such defects can be revealed by resistance measurements and therefore, the D.C. resistance (also known as ohmic resistance) of the windings is measured in all transformers that have

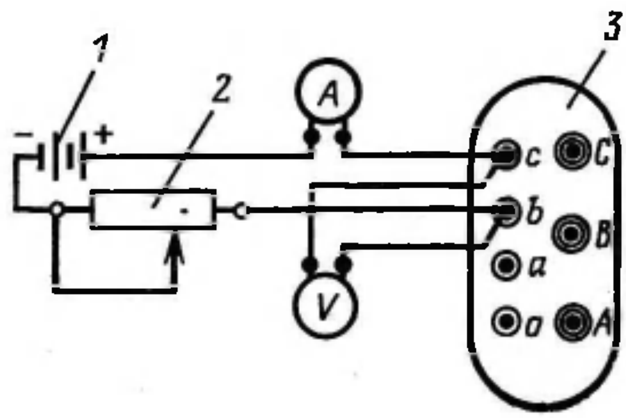


Fig. 8.7. Diagram for measuring the D.C. insulation resistance of the windings by the drop-of-potential method

1—4- to 6-volt storage battery; *2*—current-control rheostat; *3*—transformer tank cover with terminal bushings

underwent major repair. The measurement results obtained for all phases and voltage-control steps must not differ by more than 2%.

When measuring resistances, the temperature of the windings must be taken into account.

Figure 8.7 shows a diagram of measuring the D.C. resistance of the windings by the drop-of-potential method which is based on Ohm's law.

8.5. Measuring the No-Load Current and the No-Load and Short-Circuit Losses

Various defects in the magnetic circuit of the transformer cause an increase in the no-load current and losses and hence, reduce the efficiency of the transformer, and may lead to excessive overheating.

To check the transformer for such defects, its actual no-load (exciting) current and losses are measured and compared with the design data. For this purpose the no-load

loss and exciting-current tests are made. One of the transformer windings (usually the LV one) is excited with a symmetrical 50-Hz voltage that is gradually raised from zero to the rated value. The HV winding is left open-circuited. The active power consumed by the transformer is measured with a wattmeter and the line currents, with ammeters. The test is frequently made at a lowered, rather than rated, voltage and the test results are then corrected to the rated voltage.

Wrong transposition of the conductors in the windings, breaks and fractures in the parallel conductors, the use of conductors of wrong section, bad contacts—all such defects, that may occur when repairing transformers, especially if the replacement of the windings and re-soldering of connections are involved, cause an increase in the winding resistance and consequently, an increase in the load losses of the transformer.

To reveal such defects, the short-circuit test is made: the actual losses in the windings are determined and then compared with the design data. In this test, the terminals *a*, *b*, and *c* on the LV side are short-circuited by means of a copper jumper, and a voltage is applied to the HV winding terminals and adjusted to circulate rated currents in the windings. It is also permissible to make the test at a lower voltage, but only on condition that the currents in the windings are not less than 25% of the rated ones. In this case, the measurement results are corrected to the rated currents.

Reference tables usually list the load losses at a winding temperature of 75°C. Therefore, the winding temperature is measured during the test and the necessary corrections are then made.

The measurement results are compared with the design data, and should the load losses prove to be increased, this means that there is a defect in the transformer.

8.6. Determining the Insulation Characteristics

When measuring the insulation resistance of the windings and the dielectric strength of the oil, as well as in other instances, a question may arise as to whether the transformer

Table 8.4

Maximum Permissible Values of Insulation Characteristics for Transformer Windings*

Transformer voltage class and capacity	Insulation characteristic	Winding temperature, °C						
		10	20	30	40	50	60	70
Up to 35 kV inclusive with a capacity of 10 000 kV A and over; 110 to 220 kV irrespective of capacity	tan δ, %	1.8	2.5	3.5	5	7	10	14
330 to 500 kV irrespective of capacity	tan δ, %	1	1.3	1.6	2	2.5	3.2	4
Up to 35 kV inclusive irrespective of capacity	C_2/C_{50}	1.2	1.3	1.4	1.5	1.6	1.7	1.8
110 to 150 kV irrespective of capacity	C_2/C_{50}	1.1	1.2	1.3	1.4	1.5	1.6	1.7
110 kV and over irrespective of capacity	$\Delta C/C$	8	12	18	29	44	—	—
	Difference in $\Delta C/C$ between the end and the start of repair, i.e. $(\Delta C/C)_f - (\Delta C/C)_i$, corrected to the same temperature	3	4	5	8.5	13	—	—

* The listed data refer to all transformer windings.

insulation is moist. In such cases, the following additional insulation characteristics are determined: the loss tangent, the ratio between the winding capacitances measured at 2 and 50 Hz, i.e., C_2/C_{50}, and the winding capacitance increment, i.e., $\Delta C/C$.

The ratio C_2/C_{50} is measured by means of the Model ПКВ moisture-testing instrument. Its operation is based on the principle of measuring the transformer winding capacitances at frequencies of 2 and 50 Hz. The difference between these capacitances depends on the moisture content of the insulation.

For transformers in actual service the above characteristics must comply with the data given in Table 8.4.

Table 8.5

Requisite Conditions for Putting Overhauled Transformer Into Service Without Drying-Out or Test Drying

Transformer voltage class and capacity	Insulation characteristics
Up to 35 kV inclusive with a capacity of up to 10 000 kV A inclusive	$R_{60''}$—must not decrease during repair by more than 50% of the value specified by the manufacturer, or must not be lower than indicated in Table 8.2 $R_{60''}/R_{15''}$—must not be lower than 1.3 at a temperature of 10 to 30°C
Up to 35 kV inclusive with a capacity of more than 10 000 kV A; 110 kV and over irrespective of capacity	$R_{60''}$—must not decrease during repair by more than 40% of the value specified by the manufacturer, or must not be lower than indicated in Table 8.2 $R_{60''}/R_{15''}$—must not be lower than 1.3 at a temperature of 10 to 30°C $\tan\delta$—must not increase during repair by more than 30% of the value specified by the manufacturer, or must not be higher than indicated in Table 8.4 C_2/C_{50}—must not increase during repair by more than 20% of the value specified by the manufacturer, or must not be higher than indicated in Table 8.4 $\Delta C/C$—must not be higher than indicated in Table 8.4

Determining the above insulation characteristics after repair and comparing them with the data obtained prior to repair and with the standard data enable one to judge of the condition of the transformer insulation and of the possibility of putting the transformer into service without drying-out or test drying. A repaired transformer can be put in operation without drying-out or test drying if its insulation characteristics are in agreement with the data given in Table 8.5.

Review Questions

1. What are the measurements to be taken when finally testing a transformer after repair?
2. How is the suitability of the transformer oil for operation determined?
3. Tell about the methods and circuit connections used for measuring the insulation resistance of the transformer windings.
4. What are the insulation characteristics determining the quality of the transformer insulation?

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